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IMPACT OF CIRCULAR AGRICULTURE ON THE SUSTAINABILITY OF THE COCOA VALUE CHAIN IN BOYACÁ, COLOMBIA

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ABSTRACT OF THE THESIS

IMPACT OF CIRCULAR AGRICULTURE ON THE SUSTAINABILITY OF THE COCOA VALUE CHAIN IN BOYACÁ, COLOMBIA

Lizeth Maholy Hurtado Albarracin, 2025

Keywords: Cocoa value chain; Circular agriculture; Sustainability; Cocoa waste; Smallholders.

Cocoa *(Theobroma cacao L.)* is one of the most widely traded commodities on the global market, which has led to a significant expansion in cultivated areas and production volumes. According to the International Cocoa Organization (ICCO), Colombia is the tenth largest producer worldwide. This is due to the implementation of illicit crop substitution programs such as "Cacao para la paz" and "Familias Guardabosques". The aim of these programs was to promote the switch from coca to cocoa. While this shift in agricultural practices has led to an increase in cocoa production and an improvement in the quality of life for smallholders, the sustainability of this value chain remains a concern due to the ongoing development of agricultural activities in a linear flow.

The prevailing linear economic model has exerted a significant influence on the cocoa value chain, giving rise to several salient issues. These include an increased demand for raw materials and external inputs, as well as a dearth of effective waste management strategies. The transition to a circular agriculture model has emerged as a viable alternative, as evidenced by mounting research findings that have demonstrated successful outcomes through case studies at various links in the value chain. This research, supported by this alternative, analyzed the impact of circular agriculture practices on the sustainability of the cocoa value chain in the department of Boyacá.

The research was conducted using the RECOIN methodology, which included a literature review to identify common variables between circular agriculture and sustainability in the cocoa value chain; a survey administered to 24 smallholders; a Principal Component Analysis; and three focus groups with smallholders. The research methodology comprised two semi-structured interviews, one with a

technician and one with a director of the cocoa value chain. Triangulation was utilized to select the circular agriculture practice and its action point. A product analysis was conducted on a food by-product made of cocoa organic matter, and a participatory mapping was employed to identify proposals for interaction between smallholders and their territory around the selected action point.

The findings indicated a favorable impact of the selected circular agriculture practice, reduction of waste generated, and the action point, use of organic matter, on the sustainability of the cocoa value chain in the department of Boyacá. From an environmental perspective, 278.91 liters of mucilage juice per hectare were utilized, which used to be classified as waste. From an economic standpoint, the potential marketing of a food by-product represented 24% of the income received from selling cocoa beans in 2024, with a profit margin of 27%. From a social perspective, two working groups on the use of cocoa waste were established in two of the three participating associations, and four agrotourism routes were proposed for the dissemination of knowledge related to the cocoa waste processing.

RESUMEN DE LA TESIS

IMPACTO DE LA AGRICULTURA CIRCULAR EN LA SOSTENIBILIDAD DE LA CADENA DE VALOR DEL CACAO EN BOYACÁ, COLOMBIA

Lizeth Maholy Hurtado Albarracin, 2025

Palabras Claves: Cadena de valor del cacao; Agricultura circular; Sostenibilidad; Residuos de cacao; Pequeños productores.

El cacao *(Theobroma cacao L.)* es uno de los commodities más comercializados en el mercado mundial, lo que ha llevado a una expansión significativa de las áreas cultivadas y los volúmenes de producción. Según la Organización Internacional del Cacao (ICCO), Colombia es el décimo mayor productor mundial. Esto se debe a la implementación de programas de sustitución de cultivos ilícitos como "Cacao para la paz" y "Familias Guardabosques". El objetivo de estos programas era promover el cambio de la coca al cacao. Si bien este cambio en las prácticas agrícolas ha dado lugar a un aumento de la producción de cacao y a una mejora de la calidad de vida de los pequeños productores, la sostenibilidad de esta cadena de valor sigue siendo motivo de preocupación debido al desarrollo continuo de las actividades agrícolas de forma lineal.

El modelo económico lineal predominante ha ejercido una influencia significativa en la cadena de valor del cacao, dando lugar a varios problemas destacados. Entre ellos se incluyen el aumento de la demanda de materias primas e insumos externos, así como la escasez de estrategias eficaces de gestión de residuos. La transición a un modelo de agricultura circular se ha convertido en una alternativa viable, como lo demuestran los crecientes resultados de investigaciones que han demostrado resultados exitosos a través de estudios de caso en diversos eslabones de la cadena de valor. Esta investigación, soportada por esta alternativa, analizó el impacto de las prácticas de agricultura circular en la sostenibilidad de la cadena de valor del cacao en el departamento de Boyacá.

La investigación se llevó a cabo utilizando la metodología RECOIN, que incluyó una revisión de literatura para identificar variables comunes entre la agricultura circular y la sostenibilidad en la cadena de valor del cacao; una encuesta realizada a 24

pequeños productores; un análisis de componentes principales; y tres grupos focales con pequeños productores. La metodología de investigación comprendió dos entrevistas semiestructuradas, una con un técnico y otra con un directivo de la cadena de valor del cacao. Se utilizó la triangulación para seleccionar la práctica de agricultura circular y su punto de acción. Se realizó un análisis de producto a un subproducto alimenticio elaborado con materia orgánica de cacao y se empleó un mapeo participativo para identificar propuestas de interacción entre los pequeños productores y su territorio en torno al punto de acción seleccionado.

Los resultados indicaron un impacto favorable de la práctica de agricultura circular seleccionada, reducción de los residuos generados, y la medida de acción, uso de materia orgánica, en la sostenibilidad de la cadena de valor del cacao en el departamento de Boyacá. Desde una perspectiva ambiental, se aprovecharon 278.91 litros de jugo de mucílago por hectárea, los cuales solían clasificarse como residuos. Desde el punto de vista económico, la potencial comercialización de un subproducto alimenticio representó el 24% de los ingresos obtenidos por la venta de grano de cacao en 2024, con un margen de ganancia del 27%. Desde una perspectiva social, se establecieron dos grupos de trabajo en torno al aprovechamiento de los residuos del cacao en dos de las tres asociaciones participantes, y se propusieron cuatro rutas de agroturismo para la difusión de conocimiento relacionado con la transformación de los residuos del cacao.

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1. INTRODUCTION

The current agricultural model is based on the “take-produce-consume-discard” premise of the linear economic model, which posits that economic growth can be predicated on abundant resources and unlimited waste disposal (Jurgilevich et al., 2016). This assumption has encouraged the development of unsustainable practices, which have led to dependence on monocultures, water scarcity, reduced soil fertility, excessive food waste, and inefficient use of natural resources (Ortiz Gutiérrez et al., 2021).

The lack of management in the linear model, characterized by its increasing demand for raw materials to produce goods, consequently, raises the CO_2 footprint, waste production, and causes inefficiencies in material flows, which lead to negative environmental externalities (Wautelet, 2018). These adverse effects directly affect the dimensions of sustainability: environmental, economic, and social, creating the need for a shift in the model, focused on reducing vulnerability to climate change and on restoring and conserving biodiversity (Bianchi et al., 2020).

The impacts of the linear model might be mitigated through the implementation of circular agriculture practices at the local level. Circular agriculture is based on agricultural production that exerts minimal impact on the environment and natural resources such as water, soil, and biodiversity. It includes the following objectives: reducing the number of inputs into the system, including chemical fertilizers, pesticides, and (single-use) plastics; minimizing water use; reducing emissions during production cycles; and recycling and recovering waste (Du Pré, 2020).

Circular agriculture promotes sustainable management of agricultural resources through a holistic approach that combines various practices, such as recycling waste, using bioproducts, and developing subsystems that optimize resource use and biodiversity (Selvan et al., 2023). Implementing these practices in value chain processes has been shown to produce positive impacts, including reducing raw material extraction, waste generation, and CO_2 emissions (Mayson & Williams, 2021).

Several value chains have implemented circular agriculture practices to stimulate the circular economy, as shown by van Keulen (2018) in his research on the coffee value chain, which included packaging loops, coffee sludge fertilizer, reusable coffee cups, and sustainable agriculture, leading to less waste generation and increasing the use of by-products. Specifically for the cocoa value chain in Colombia, Abbott et al. (2018) demonstrated that practices consistent with a circular economy model enhance sustainability in the cocoa production process. The researchers identified the effective management of resources as a critical component of sustainability, extending from the extraction of raw materials to the generation of waste.

1.1 Justification

In accordance with the global trend, the linear agricultural model is also predominant in Colombia, encompassing both crops managed by large and small producers. Since 2018, formal initiatives have been presented through official institutions, including international alliances on circular agriculture, such as the agreement between Colombia and the Netherlands to implement circular agriculture initiatives in the coffee, banana, flower, and palm oil value chains (Du Pré, 2020). These initiatives motivate the strengthening of other value chains, such as avocado and cocoa, which are among Colombia's agricultural products with the highest export growth.

The cultivation of cocoa has emerged as the predominant alternative to coca cultivation in Colombia. In the central-eastern region of the country, projects have been implemented that have achieved substitution but have not stopped coca planting. For instance, in the department of Boyacá, located in this region, the number of hectares planted with coca increased by 35% between 2020 and 2021 (UNODC-SIMCI, 2022). This situation indicates the need for interventions to promote substitution and integrate agricultural practices that contribute to the sustainability of the cocoa value chain.

The expansion of cocoa cultivated areas has been demonstrated to engender positive socio-economic and environmental effects, mainly due to the planting of crops in agroforestry systems. An agroforestry system is defined as a deliberate cultivation of trees or other perennial woody plants within agricultural systems that incorporate animal husbandry. The main objective of an agroforestry system is to optimize the capture and utilization of resources, including nutrients, light, and water, thereby ensuring sustainable land use and increasing net carbon (C) sequestration in soils (Lorenz & Lal, 2018).

Research such as that carried out by Peñalosa (2022), demonstrates that cocoa crops in agroforestry systems are a moderately sustainable alternative to help minimize the impacts generated by the expansion of illicit crops. The majority of cocoa crops in the Boyacá region are cultivated within agroforestry systems, which are recognized as an effective strategy for recovering degraded soils, restoring forest connectivity, mitigating the impacts of climate change, preserving biodiversity, and generating income for local communities (Rodríguez et al., 2022).

Despite the numerous advantages associated with agroforestry systems, the management of these systems by smallholders is predominantly characterized by a linear agricultural model. This research endeavors to support smallholders in integrating circular agriculture practices into their production systems, with the assistance of official institutions and decision makers. The implementation of these practices is expected to have a positive impact on the environmental, economic, and social sustainability of the cocoa value chain. Consequently, this study lays the groundwork for further research and the development of investment projects in the department of Boyacá.

1.2 Research questions

- How are circular agriculture practices related to sustainability in the cocoa value chain?
- To what extent do circular agriculture practices impact the sustainability of the cocoa value chain in Boyacá?
- How to manage circular agriculture practices in cocoa production units in the department of Boyacá?

1.3 Objectives

1.3.1 General Objective

To analyze the impact of circular agriculture practices on the sustainability of the cocoa value chain in Boyacá, Colombia.

1.3.2 Specific Objectives

- To identify the variables that relate to circular agriculture practices with sustainability in the cocoa value chain.
- To determine the circular agriculture practices that impact the sustainability of the cocoa value chain in the department of Boyacá.

- To develop action points around circular agriculture practices in the cocoa production units in the department of Boyacá.

1.4 Hypothesis

The agricultural practices of the cocoa value chain in Boyacá are carried out through a linear flow. This linear flow consists of planting, harvesting, fermenting, drying, and waste disposal, which affects the sustainability of the value chain. Several studies have shown that the unrestrained development of agricultural activities such as crop production and land expansion has contributed substantially to global warming, climate change, air pollution, and greenhouse gas (GHG) emissions (Ahmed et al., 2025).

The cost-benefit of transitioning to circular agriculture is evaluated from multiple perspectives, including economic, environmental, and social considerations. The study conducted by Padthar et al. (2024) demonstrated that social influence is a salient factor in farmers' behavior. The successful implementation of circular practices by one or a group of them has been demonstrated to engender an increase in the level of trust and intent to implement among their peers.

The circular agriculture practices are characterized by a focus on minimizing external inputs, decreasing resource requirements, regenerating bio-ecosystems, and reducing waste generated (Chung et al., 2024). The present study hypothesizes that the implementation of one or more circular agriculture practices will have a positive impact on the environmental, economic, and social sustainability of the cocoa value chain in Boyacá, Colombia.

2. FRAMEWORK

2.1 Circular agriculture

The premise of circular agriculture is based on preventing losses and waste, reusing and recycling products, maximizing the utility of materials throughout the agricultural value chain, and harnessing nutrients and biomass to produce more efficiently, thereby limiting the overuse of natural resources and the environmental pollution (Hoogstra et al., 2024). Moreover, the implementation of these agricultural practices has the potential to provide consistent benefits to the agribusiness sector. These benefits include enhanced management of raw materials, increased energy efficiency, and reduced costs, which can result in the generation of sustainable scenarios (Barros et al., 2020).

Circular agriculture incorporates principles of eco-friendly technology application, resource efficiency, and waste valorization, which support labor-intensive production practices and contribute to the reduction of chemical fertilizers, waste, and CO_2 emissions. In contrast, linear agriculture is based on large-scale business models, mostly specialized and intensive, with a focus on monocultures that require high amounts of agrochemicals and resources, which generate impacts on the ecosystem and affect human health in the short and long term (Chung et al., 2024), as shown in Table 1.

Table 1.The differences between linear and circular agriculture. Source: Chung et al., 2024.

Criteria	Linear agriculture	Circular agriculture
1. Development history	Widely practised by industrial societies	Widely practised by pre-industrial society
2. Business Model	Large-scale, specialized agricultural firms	Small-scale, integrated agriculture smallholders
3. Farming Practices	Modern farming, large-scale, monoculture, inorganic practices	Indigenous, small-scale, polyculture, bio-organic practices
4. Input use	More capital intensive with off-farm inputs	More labor intensive with on-farm inputs
5. Focus	Maximizing profit over the protection of the environment	Balancing economic, environmental, and social aspects
6. Reuse	Downcycling, low-grade recycling	Upcycling, cascading and high-grade recycling
7. Products that have reached the end of their life	Invaluable and wastes	Valuable next-use resources
8. Impacts	Increased resource requirements and waste, less sustainable	Reduced resource requirements and waste, more sustainable

The concept of a circular economy-based system has emerged as a sustainable alternative to the conventional linear model of waste management. This paradigm shift is characterized by the incorporation of processes such as reuse and recycling, along with technologies designed to minimize waste generation and enhance agricultural efficiency (Payne & Kwofie, 2024). The integration of the circular economy in the agricultural sector has been demonstrated to contribute to the well-being of farmers and small producers. This is achieved through the development of new production and marketing models, in which both large and small enterprises participate, thereby contributing to social sustainability (World Economic Forum, 2023).

Initiatives grounded in circular agriculture practices have demonstrated the capacity for transformative impact. Hoogstra et al. (2024) conducted a comprehensive analysis of 29 circular agriculture initiatives in the northern part of the Netherlands.

Their findings suggest that the implementation of social and technological innovations has led to enhanced efficiency in production systems. This, in turn, has the potential to contribute to the consolidation of a sustainable food system in the region. In Ecuador and Uganda, Tennhardt et al. (2023) examined the factors that influenced the implementation of circular agricultural practices by 394 cocoa producers. The analysis concluded that information management, producer organization, and the economic endowment of the farms are the most relevant factors to strengthen the value chain and ensure sustainable production of cocoa in the long term.

The implementation of circular agriculture initiatives in value chains promotes the connection among environmental, economic, and social dimensions, as it allows the efficient use of natural resources, the flow of materials, and the integration of value chain actors. As shown by Silvius et al. (2023) with the initiatives "Circular Broilers" and "AgriCycling", which are centered on the utilization of two distinct approaches for addressing circular agriculture. The first one focused on recycling crop residues as a source of sustenance for broiler chickens. The second one focused on reusing municipal waste streams to produce synthetic fertilizers.

2.2 Cocoa cultivation

Cocoa (*Theobroma cacao L.*) is among the ten most traded commodities worldwide, with a global market valued at USD$15.3 billion in 2022 (Glauber & Mamun, 2024). Between 2008 and 2020, its production increased by 1.49 Mt (million tons), from 4.27 Mt to 5.76 Mt (Bermudez et al., 2022). Africa is the largest producer, accounting for approximately 65% of the world's cocoa. Latin America and the Caribbean contribute approximately 15% of the global production and 80% of the world's prime cocoa (FAO, 2021).

In addition to the economic benefits, cocoa production has been shown to have positive environmental impacts due to its cultivation in agroforestry systems. The incorporation of trees, plants, and shade crops within cocoa systems has been demonstrated to enhance the microclimate and soil conditions within the production unit (Bosselmann et al., 2024). As the FAO (2020) points out, natural shade plays a critical role in preserving and safeguarding biodiversity, curbing deforestation, and mitigating greenhouse gas (GHG) emissions. Agroforestry systems have been shown to be more effective than monoculture systems in terms of solar energy utilization and the provision of ecosystem services associated with climate maintenance, carbon sequestration, and nutrient cycling (Pérez-Neira et al., 2023).

On a global scale, 95% of the cocoa supply is derived from small-scale farmers who own between two and five hectares of land and employ between five and six million cocoa farmers in Asia, Africa, Oceania, and Latin America (Suh & Molua, 2022). The average income of these farmers is estimated to be less than one dollar per day. Consequently, the majority of cocoa farmers subsist below the poverty line (Kalischek et al., 2023).

In Colombia, the cocoa planted area and production have increased by 29% and 41% respectively, with a national average yield of approximately 450 kilograms per hectare (Minagricultura, 2020). This growth can be attributed, at least in part, to increased exports, which rose from 7,056 tons in 2018 to 11,689 tons in 2021 (Fedecacao, 2022). Concerning the commercialization of cocoa beans and their derivatives, the export increased from USD$125.3 million FOB (Free On Board) in 2021 to USD$131.1 million FOB in 2022. Furthermore, sales were documented for USD$39.2 million FOB in the first quarter of 2023, with principal destinations being Mexico, Belgium, and the United States (Procolombia, 2023).

Many of the areas currently used for cocoa cultivation were formerly coca growing areas with a strong presence of illegal groups that caused severe social problems such as poverty, unemployment, and violence (Minagricultura, 2020). The increase in international demand, coupled with the implementation of crop substitution strategies at the national level, has facilitated a transition by smallholders from illegally cultivated coca to legally cultivated cocoa. This transition has resulted in significant economic and social improvements in affected regions, leading to cocoa being recognized as "The Peace Crop". The results of the substitution strategies show that over 40% of the national cocoa production comes from crops that were previously dedicated to coca cultivation (Vargas et al., 2023).

Regarding environmental conditions, most cocoa crops in Colombia are cultivated in agroforestry systems that emulate the natural conditions under which this tropical humid forest originally evolved. The accompanying cocoa species fulfill a dual role, providing moderate shade to the cocoa crop for its optimal development and generating income for smallholders in both the short and long term (J. Arenas, 2020). The presence of shade trees has been shown to promote biodiversity within crops, enhance soil quality, conserve water resources, and sequester carbon. Additionally, they facilitate connectivity between forest patches and, depending on the forest species selected, contribute to ecological restoration (W. Arenas et al., 2020).

In Colombia, 95% of the productive social base of the cocoa sector is classified as smallholders, with an average of three hectares of cocoa per producer, making up a total of approximately 65,341 families, distributed in 27 departments and 422 municipalities (Minagricultura, 2021). The participation of the family in daily agricultural activities is a hallmark of cocoa cultivation, facilitating the involvement of all family members. However, it is evident that the majority of cocoa producers are men, with a representation of 72.7%, while women represent 27.3% (Vargas et al., 2023).

Agroforestry systems exemplified by the "Cocoa, Forests and Peace" initiative in the Amazon demonstrate the viability of a cocoa value chain that is deforestation-free, integrating water management, conservation, and forest restoration (Alisos & Bosque & Paz, 2023). This initiative demonstrates that, due to the existing linkages among the components of an agroforestry system, it is a potential system for implementing circular agriculture practices. This is because it allows efficient management of resources and waste generated, as well as materials flow.

2.3 Cocoa value chain

The cocoa value chain includes tangible and intangible activities carried out by linked actors and stakeholders to obtain cocoa beans and derivatives for delivery to consumers. As shown in Figure 1, the process begins with the planting of trees in tropical environments, which, after five years, yield cocoa pods. The cocoa pods are extracted from the tree, opened and shelled; the mucilage is separated from the bean, which is then fermented for a period of three to seven days.

Following the fermentation process, the beans undergo a drying procedure. This can be either natural, occurring through sun-drying, or artificial, involving the use of a mechanical dryer. Once dried, the cocoa beans are packaged into sacks for sale to a local station or purchasing agent, who transports the sacks to an exporting company. When the bags arrive at their destination, the cocoa beans undergo a roasting and grinding process to yield a range of products, including cocoa liquor, cocoa powder, cocoa paste, and cocoa butter. These products are predominantly utilized in the production of chocolate (Putri et al., 2015).

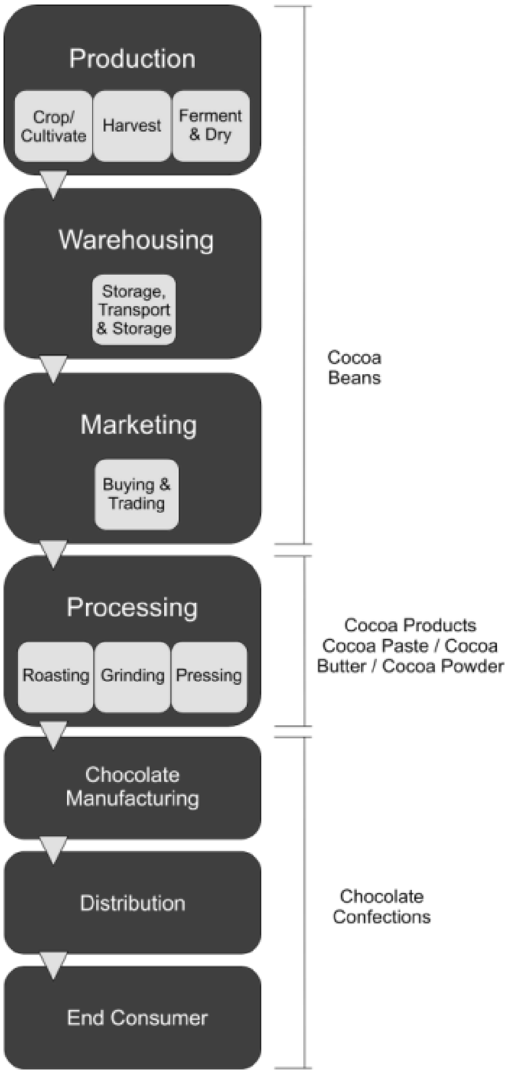

Figure 1. Cocoa value chain, global context. Source: Putri et al., 2015.

The main support of the cocoa value chain are small producers, whose global income is insufficient to ensure adequate living conditions. Research conducted in Africa, the world's largest producer, indicates that between 30% and 58% of smallholders in Côte d'Ivoire and Ghana derive incomes below the World Bank's extreme poverty line (van Vliet et al., 2021). A similar situation is observed in Ecuador, where large companies control the market, creating an imbalance of power in the negotiation and disintegration of small producers in the cocoa value chain (Viteri Salazar et al., 2023).

In Colombia, 95% of the cocoa produced is classified as "fine or flavor". This contrasts with the global production of this category, which is 5%. This distinction contributes to its high demand in the global market (Proyecto ColombiaMide, 2021). The cocoa value chain in Colombia comprises five links, as illustrated in Figure 2. This research focused on the initial two links, which include agricultural activities. The products obtained from these two links are dry cocoa beans, which continue their flow to the next links, and organic matter, which is classified as waste and ends its flow in the second link. This sequence indicates that the value chain prioritizes dried beans and their derivatives but does not incorporate products derived from other parts of the cocoa pod.

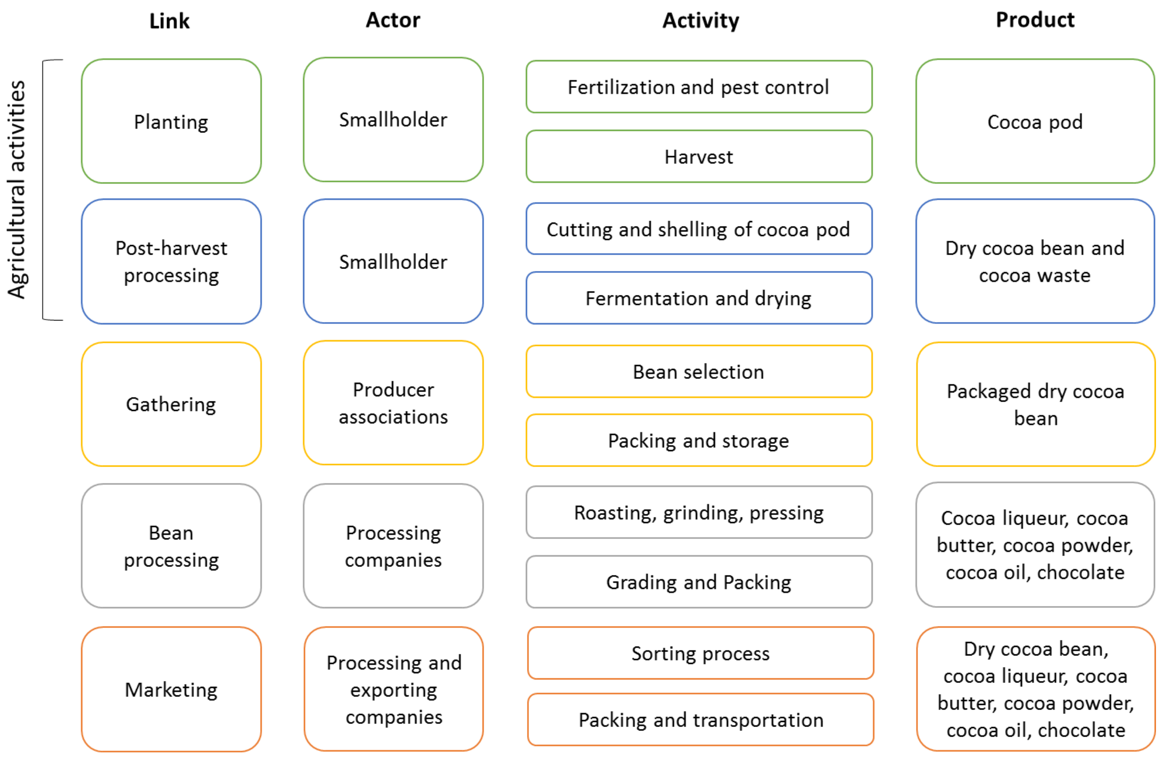

Figure 2. Cocoa value chain in Colombia. Source: Own elaboration based on Proyecto ColombiaMide, 2021.

On a national scale, the cultivation of cocoa is the second most important after coffee, being the main source of income for more than 50,000 families in the country, which are mainly composed of smallholders with poor living conditions. Studies such as Charry et al. (2025) have demonstrated that in Colombia, Ecuador, and Peru, the income per hectare per year received by smallholders is below the poverty line. Roldan et al. (2013) point out that the smallholders are the weakest link in the value chain, which is partly due to non-integration with other actors in the chain. It is so, as most of them have little or no contact with stakeholders, especially with chocolate manufacturers.

2.4 Circular agriculture and sustainability of the cocoa value chain

The circular economy in agriculture focuses on developing models and tools to close resource loops and keep materials within the agri-food system for as long as possible. Particularly, circularity in the cocoa value chain has been approached from four main aspects, such as climate change and carbon sequestration; agroecological production alternatives; complementary biofertilizers; and waste management as an alternative for environmental, economic, and social sustainability (Carvajal et al., 2023).

Among the strategies for promoting circularity are the implementation of agroforestry systems, eco-design and remanufacturing of products, controlled technification, water and energy recirculation, transformation of waste into by-products, and promotion of organizational alliances (Carvajal et al., 2023). Adopting these strategies could help reduce deforestation practices in regions where cocoa plantations have expanded due to increased global demand, such as Côte d'Ivoire, where 46% of deforestation is attributed to cocoa production (Olarte Libreros et al., 2025).

The implementation of circular practices in cocoa cultivation has demonstrated a positive impact on the well-being of local communities. Research such as that conducted by Fisher-Ortíz et al. (2022) demonstrated that applying practices with a circular approach promotes ecosystem resilience by combining traditional and modern techniques in agroforestry systems. Successful cases such as Côte d'Ivoire, where native vegetation has been successfully regenerated and diversity preserved. Ghana, where there is evidence of reduced disease in crops (Jagoret et al., 2020). Ecuador, where the circular management of crops in agroforestry systems has restored watersheds, preserved indigenous territory, and increased leadership by women and young people (World Centric, 2022).

Research that has addressed the link between circular agriculture and sustainability in the cocoa value chain has demonstrated, through case studies, the minimization of waste and the maximization of resource efficiency. Outstanding studies on the potential of cocoa pod husks for the manufacture of organic fertilizers, biochar, bioadsorbents, and bio-ink in tissue engineering. It also highlights the manufacture of food products, which, being a result of circular processes, are well accepted by consumers (Izzah et al., 2023; Girón-Hernández et al., 2024; Aschemann-Witzel & Peschel, 2019).

Business models grounded in circularity within the cocoa production system generate marketing opportunities that benefit all actors involved in the value chain. The cost-benefit ratio of new alternatives for the management of cocoa resources and residues is generally positive, representing an added value for smallholders (Hoof et al., 2024). Participation of public and private institutions in the implementation of new alternatives is a critical point for obtaining financial support and access to markets, as indicated by the Inter-American Institute for Cooperation on Agriculture, investments in sustainable practices can be profitable and beneficial to the environment, economy and society (Olarte Libreros et al., 2025).

3. STUDY AREA

3.1 Geographical description

Boyacá is one of Colombia's 32 departments. Its precise geographical location is defined by the following coordinates: Latitude north, 7° 08' north, in the vicinity of the department of Santander (Cobugón River); and 4° 39' south, in the vicinity of the department of Cundinamarca (Guavio River). Longitude west of Greenwich, 71° 56' east, within the geographical confines of the department of Arauca, specifically along the Bojabá River; and 74° 38' west, marking the boundaries of the department of Magdalena, characterized by the presence of the Negro River (Gobernación de Boyacá, 2012).

The department is situated in the central-eastern part of the country, encompassing an area of 2,277,667 ha characterized by a variety of land uses. The most prominent are agricultural land, covering 1,542,268 ha (67.7%); followed by natural forests with 618,532 ha (27.2%); non-agricultural areas with 82,367 ha (3.6%); and other uses and land cover occupying the remaining 34,500 ha (1.5%) (DANE, 2016).

Boyacá is composed of 123 municipalities, which are grouped into 13 provinces: Centro, Gutiérrez, La Libertad, Lengupá, Márquez, Neira, Norte, Occidente, Oriente, Ricaurte, Sugamuxi, Tundama, and Valderrama; a special management area and a border district (Gobernación de Boyacá, 2020b). The western province, comprising the municipalities of Briceño, Caldas, Buenavista, Chiquinquirá, La Victoria, Coper, Maripí, Otanche, Muzo, Pauna, Saboyá, Quípama, San Miguel de Sema, Tununguá, San Pablo de Borbur, and the special management area of Puerto Boyacá, has been identified as the region with the highest cocoa production (Perea & Charry, 2023), as shown in Figure 3.

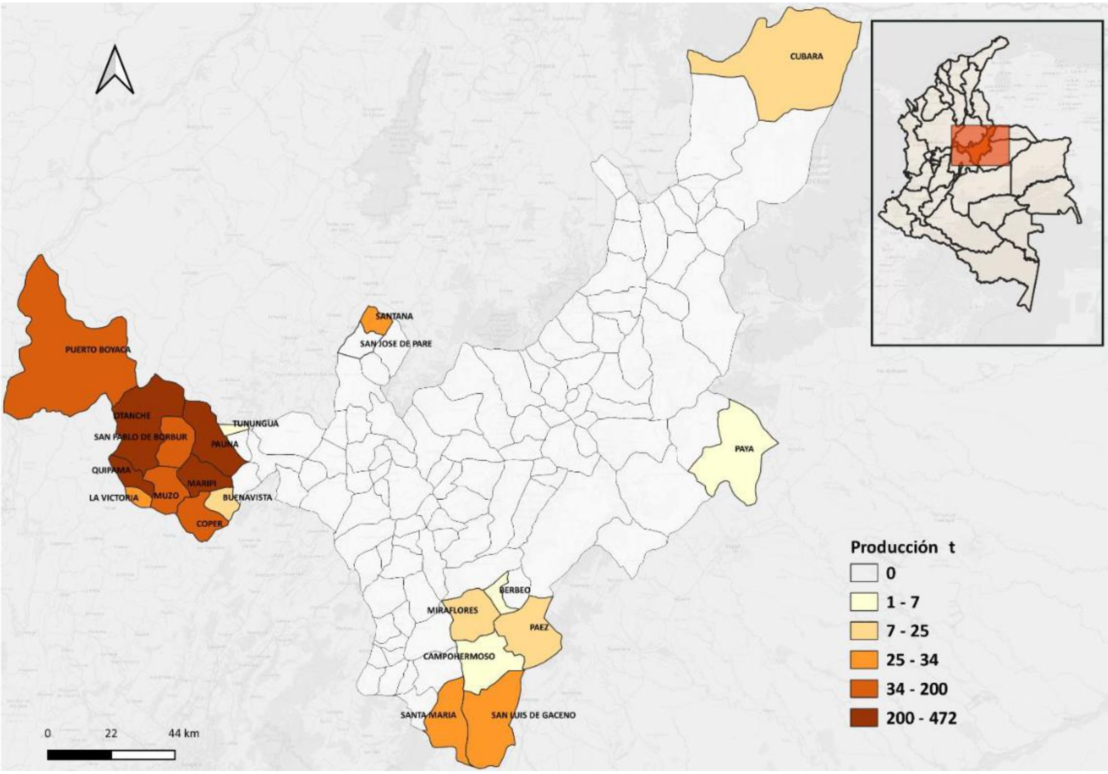

Figure 3. Cocoa production by municipalities in Boyacá. Source: Perea & Charry, 2023.

Among the municipalities with higher cocoa production, the Otanche-San Pablo de Borbur-Pauna corridor, located in the west of the department, stands out. This area was selected as the study area for this research, as indicated in Figure 4. Agriculture constitutes the primary economic activity of this region, with complementary activities such as livestock and fish farming. The implementation of cocoa as an alternative agroforestry project to replace coca cultivation emerged with CONPES 3218 of 2003 "Programa de Desarrollo Alternativo 2003 – 2006", and continued with the programs "Familias Guardabosques" and "Más Inversión para el Desarrollo Alternativo Sostenible". Cocoa associations were subsequently established in each of the municipalities (Pineda, 2018).

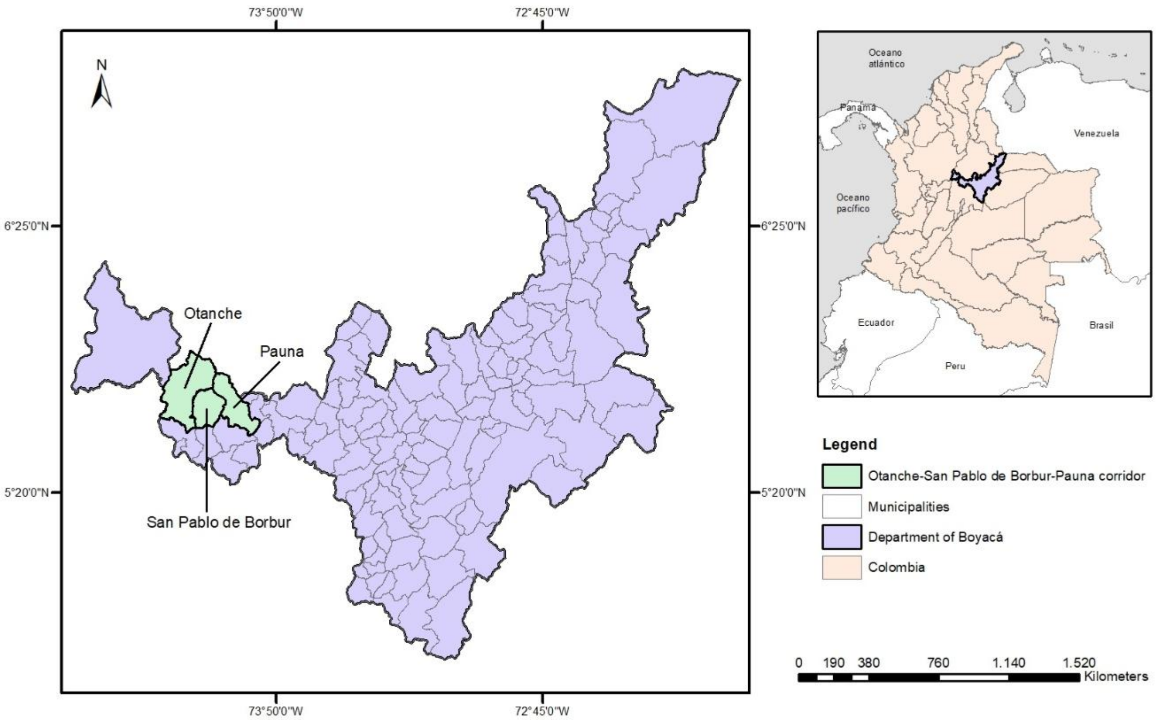

Figure 4. Geographic location of the study area. Source: Own elaboration.

Otanche has an area of 512 km^2, an altitude of 1,050 masl, and an average temperature between 23°C and 25°C. In the northern direction, it is adjacent to the municipalities of Florián, La Belleza, and Bolívar. In the southern direction, it is bordered by Yacopí. To the west, it is bordered by Puerto Boyacá, and to the east, it is bordered by the municipalities of San Pablo de Borbur and Pauna. The region's topographical characteristics include Serranía de las Qinchas, Alto del Cuy, and Mojón de Sevilla. Otanche is drained by two primary tributaries, the Magdalena and the Negro rivers. The topography is marked by a significant number of ravines, including those known as Los Mártires, La Cobre, and Nacuamás (Alcaldía de Otanche, 2024).

San Pablo de Borbur covers an area of 194 km^2, is situated at an altitude of 830 masl, and has an average temperature ranging from 21°C to 35°C. It borders the municipalities of Otanche and Pauna to the north. To the south, it borders Muzo. To the west, it is bordered by Otanche, and to the east, by Pauna and Maripí. The region's topography includes hills such as Fura, Tena, Coscuéz, and Peñas Blancas. San Pablo de Borbur is drained by two main tributaries, the Minero and the Guaso rivers. The landscape features many ravines, including Caco, Tambrías, and Honda (Alcaldía de San Pablo de Borbur, 2018).

Pauna has an area of 259 km^2, an altitude of 1,000 masl, and an average temperature between 20°C and 28°C. The municipality is bordered by the department of Santander in the northern region. In the southern direction, it is bordered by the municipalities of Caldas and Maripí. To the west, it is bordered by the municipalities of San Pablo de Borbur and Otanche, and to the east, it is bordered by the municipalities of Briceño and Tunungúa. Pauna is drained by two primary tributaries, the Minero and the Ibacapí rivers. The topography is marked by a significant number of ravines, including those known as Manotera, Guas, and Paunera (Alcaldía de Pauna, 2019).

3.2 Socio-economic description

The department of Boyacá has 1,298,800 inhabitants, with a population density of 56 people/km^2. The urban area is inhabited by 786,220 individuals, while the rural area is home to 512,580. Access to public services for rural dwellers is not yet guaranteed; the availability of natural gas is 12.3%, sewage 9.9%, and waste collection 13.4%. In urban areas, access to natural gas, sewage, and waste collection is 94.4%, 99.6%, and 100%, respectively (UPRA Boyacá, 2023).

Economic activities carried out in rural areas, such as agriculture, livestock, hunting, forestry, and fishing, occupy the second position of importance in the department. In the Otanche municipality, agricultural support activities constitute the predominant employment sector, accounting for 95%. This is followed by post-harvest activities, which generate 2.5%, and wood extraction, which accounts for an additional 2.5% (CCT, 2020). In San Pablo de Borbur, the predominant job-creating activity is agriculture, given that the rural area accounts for 87.4% of the total population of the municipality (Jiménez, 2021).

In the municipality of Pauna, agro-industrial activities play a pivotal role in supporting the production system with small-scale crops such as cocoa, citrus fruits, bananas, cane, and flowers. Research conducted by Quiroga et al. (2022) demonstrates that agrotourism has considerable potential as an economic development strategy, compelling farmers to devise productive projects within their respective regions and reduce migration. Rural-urban migration processes have developed in the region owing to substandard housing conditions, limited access to education and employment opportunities, which has led to a decline in population in rural areas (Corpoboyacá, 2016).

The economic development of the region depends on improving the living conditions for rural inhabitants. This assertion is substantiated by the incidence of multidimensional poverty, which indicates that 42% of the impoverished population of the department resides in rural areas (Gobernación de Boyacá, 2021). In response to these challenges, smallholders have adopted collective action through the formation of associations, which offer support and assistance to members. In western Boyacá, the network "Fundación Red Colombia Agropecuaria - FUNREDAGRO" unites 11 associations of cocoa smallholders (Pineda, 2018), which are shown in Table 2.

Table 2. Associations affiliated with FUNREDAGRO. Source: Own elaboration based on Rodríguez, 2019; Pineda, 2020.

Municipality	Name of the association	Year of foundation	Number of associates
Muzo	Asociación de Productores de Cacao del Municipio de Muzo “MUZCACAO”	2002	98
Quípama	Asociación de Productores de Cacao del Municipio de Quípama “APROCQUIPAMA”	2004	80
San Pablo de Borbur	Asociación Campesina de Cacaocultores de San Pablo de Borbur “ASOCACABO”	2004	80
Pauna	Asociación de Productores de Cacao del Municipio de Pauna “APROCAMPA”	2005	136
Otanche	Cooperativa Integral de Productores Agropecuarios de Otanche “CIPAOTANCHE”	2005	90
Otanche	Cooperativa Multiactiva de Familias Guardabosques Reverdecer Betania “COOPREVERDECER”	2005	56
Maripí	Asociación Campesina Agropecuaria de Maripí “ASOCAM”	2006	120
Coper	Asociación Agropecuaria de Productores de Cacao de Coper “EL MANANTIAL”	2006	72
Muzo	Sociedad Agraria Cacaotera “SAT Nueva Gema” del Municipio de Muzo	2006	112
Buenavista	Asociación de Productores de Cacao del Municipio de Buenavista “ASOBUENCACAO”	2008	38
Maripí	Asociación Campesina Paz y Progreso de Maripí, “ASOCAPAZ”	2011	55

The coordination of these associations is based not only on aspects of cocoa production and marketing but also on mutual trust and a shared sense of rooting for the territory to promote development in the region (Rodríguez, 2019). The establishment of partnerships through networks such as FUNREDAGRO facilitates the dissemination of programs, access to logistic platforms, and the establishment of alliances with research centers and institutions at the international level (Pineda, 2020).

4. METHODOLOGY

The present study developed the RECOIN methodology, a mixed research approach that involved the phases of Revision, Collection, and Interaction. The integration of quantitative and qualitative techniques was executed through eight steps, as depicted in Figure 5, to achieve the research objective.

The simultaneous consideration of quantitative and qualitative analyses allows the development of a flexible and adaptable conceptual framework that leads to a sufficiently deep and broad answer to the research question (Dawadi et al., 2021). Recent environmental studies that address agricultural dynamics and sustainability present a growing use of mixed research approaches due to the integration of the environmental, economic, and social dimensions, the inclusion of various information sources, the data contrast, and the comprehensive analysis from multiple perspectives (File & Nhamo, 2023; Perdana et al., 2023).

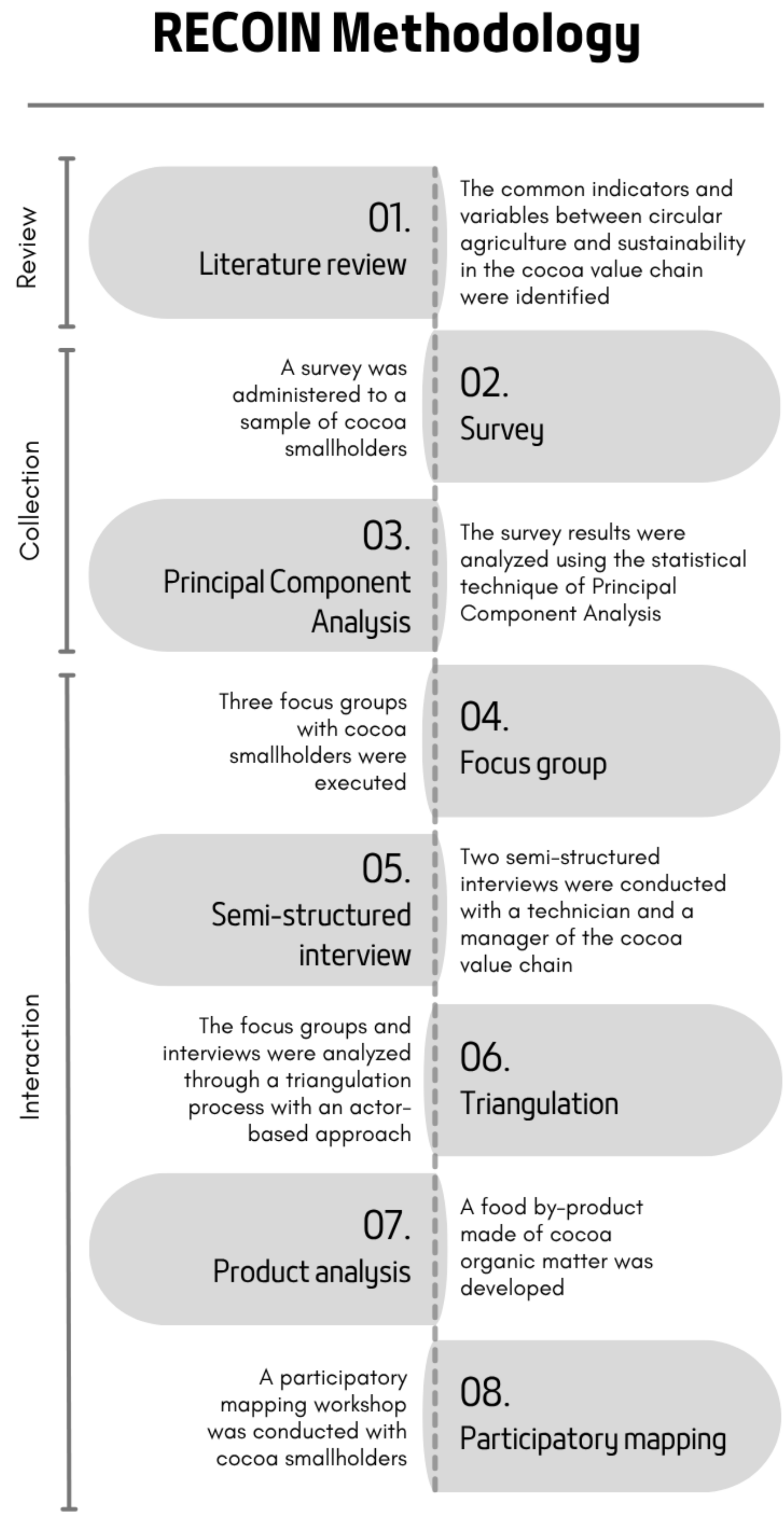

Figure 5. Steps of the RECOIN methodology. Source: Own elaboration.

The initial phase of the study was the review phase. This phase entailed conducting a literature review grounded in the review of scientific articles. The objective of this step was to identify the common variables and indicators between circular agriculture and sustainability in the cocoa value chain.

The data collection phase integrated the second step, a survey, and the third step, a statistical analysis. The survey was administered to 24 cocoa smallholders from the Otanche-San Pablo de Borbur-Pauna corridor. After the implementation of the survey, the results were subjected to analysis through the statistical technique of Principal Component Analysis.

The interaction phase with the research subject was comprised of the following five steps. The fourth step included the conduction of three focus groups with cocoa smallholders in the Otanche-San Pablo de Borbur-Pauna corridor. In the fifth step, two semi-structured interviews were integrated. These interviews were conducted with a technician and a manager of the cocoa value chain. The sixth step entailed the analysis of focus groups and interviews through a triangulation process with an actor-based approach.

In the seventh step, a food by-product made of cocoa organic matter was developed and analyzed from both a chemical and economic perspective. The development of this initiative was predicated on the selected action point about the use of organic matter generated in each of the production units of the cocoa smallholders. The eighth step entailed a participatory mapping with cocoa smallholders of the Otanche-San Pablo de Borbur-Pauna corridor. The objective of this step was to identify, through a map, proposals for interaction between smallholders and their territory regarding the marketing of the new product developed.

4.1 Literature review

A comprehensive literature review was conducted to identify common variables and indicators between circular agriculture practices and sustainability in the cocoa value chain. The initial search was executed within the Scopus database, encompassing 10 years from 2014 to 2024. The search equation employed was as follows: ALL (circular AND agriculture AND practices AND cocoa AND value AND chain AND sustainability AND environmental AND economic AND social) AND

PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")). Consequently, 141 scientific articles satisfied the established criteria.

To refine the initial results, the search equation was augmented by the inclusion of the criteria "variable or indicator": ALL (circular AND agriculture AND practices AND cocoa AND value AND chain AND sustainability AND environmental AND economic AND social AND variable OR indicator) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")). As a result, 80 scientific articles met the required parameters to undertake the review and develop quantitative and qualitative data collection instruments.

4.2 Survey

The definition of the representative research sample of cocoa smallholder production units was determined by implementing the purposive sampling technique, a non-probabilistic sampling technique that entails the selection of a group of participants based on the characteristics of the population and the objectives of the research. The selection criterion focused on two characteristics: being a cocoa smallholder and working in a production unit in the Otanche-San Pablo de Borbur-Pauna corridor.

Following the implementation of the purposive sampling technique, a representative research sample of 24 cocoa smallholders was defined, with one smallholder selected from each production unit. This sample aligns with the findings of a literature review of research with case studies related to the cocoa value chain and sustainability, which documented a sample range between 18 and 45 participants (Nguyen, 2014; Vásquez, 2023; Wibowo et al., 2021; Peñalosa, 2022).

The sampling frame of the research was based on the random selection of smallholders, thereby ensuring the participation of smallholders from different geographical points of each municipality in the Otanche-San Pablo de Borbur-Pauna corridor, as illustrated in Figure 6.

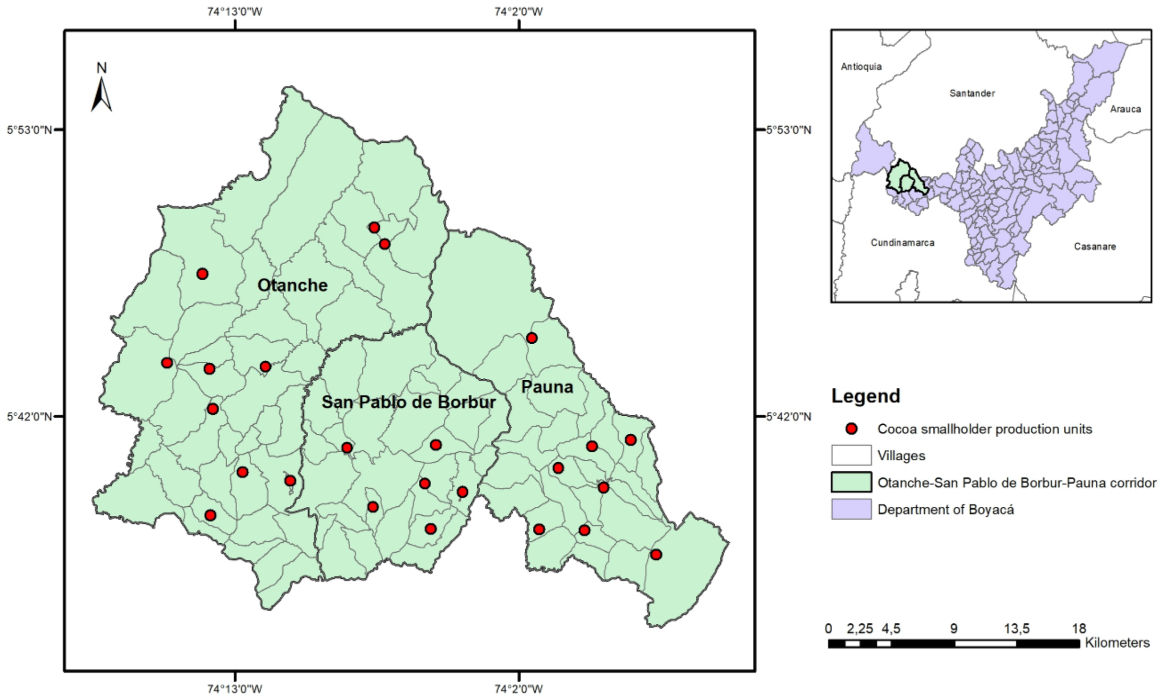

Figure 6. Geographical location of the selected cocoa production units. Source: Own elaboration.

The inclusion of women in the sample was required to promote their participation in agricultural activities. This is because most cocoa producers in Colombia are male. This suggests that the integration of women in projects related to cocoa could lead to the diversification and strengthening of cocoa cultivation perspectives. The sample also included smallholders associated and not associated with any of the three main associations in the corridor (see Table 3), which made it possible to analyze the importance of associativity in production processes.

Table 3. Associations of the Otanche-San Pablo de Borbur-Pauna corridor. Source: Own elaboration.

Municipality	**Name of the association**	**Year of foundation**	**Number of partners**
Otanche	CIPAOTANCHE -Cooperativa Integral de Productores Agropecuarios de Otanche-	2005	90 smallholders with an average of 2.5 hectares each
San Pablo de Borbur	ASOCACABO -Asociación Campesina de Cultivadores Agropecuarios de San Pablo de Borbur-	2004	80 smallholders with an average of 2.5 hectares each
Pauna	APROCAMPA -Asociación de Productores de Cacao del Municipio de Pauna-	2005	136 smallholders with an average of 2 hectares each

The analysis of the correlation between variables and indicators, as discussed in the literature review, enabled the development of a survey instrument comprising 60 questions distributed into environmental, economic, and social dimensions. The survey was conducted with 24 selected cocoa smallholders from 10 production units in the municipality of Otanche, 6 units in San Pablo de Borbur, and 8 units in Pauna.

4.3 Principal Component Analysis

The Principal Component Analysis (PCA) integrated three steps. The initial step was to standardize the model variables, which correspond to the indicators identified in the literature review. After the standardization of these variables, a normality analysis was conducted for each dimension to determine whether the variables followed a normal distribution. The Shapiro-Wilk normality test with a significance level of 0.05 was utilized for this purpose. This test is employed to ascertain normality when the sample size is less than 50, a scenario that was applicable to this research, which involved a sample of 24 cocoa production units.

The second step entailed conducting a correlation analysis. This analysis was based on the results of the Shapiro-Wilk normality test, which demonstrated that in each of the environmental, economic, and social dimensions, the data did not have a normal distribution. These results indicated that the most appropriate method to execute the correlation analysis was the Spearman method, a non-parametric statistical method that measures the degree of association between variables. The Spearman method is used with data that do not have a normal distribution.

The third step entailed the implementation of Principal Component Analysis, a data transformation technique that utilized the variables selected in the second step, which met the established correlation criteria. This technique involves the execution of linear combinations, with the selection of those that exhibit maximum variance. These combinations are referred to as Principal Components (PC), and they encapsulate the informative content of the original data set.

4.4 Focus group

A focus group was conducted in each of the municipalities along the Otanche-San Pablo de Borbur-Pauna corridor. The primary objective of the focus group is to furnish the moderator with insights regarding the knowledge, opinions, beliefs, and feelings of the participants concerning specific subjects (Conejero S, 2020).

The focus group in the municipality of Otanche (see Figure 7) included nine smallholders (four women and five men); in the municipality of San Pablo de Borbur, five people (three women and two men); and in the municipality of Pauna, seven participants (seven women). Most of the smallholders were between the ages of 27 and 59, and they consented to participate in the focus group by signing an informed consent form. This form included a provision that authorized the recording and photographing of the activities.

Figure 7. Focus group in the municipality of Otanche. Source: Own elaboration.

The focus group framework was supported by the results of the statistical analysis of the survey administered to 24 cocoa smallholders. The questions for each dimension were formulated to align with the variables prioritized in the Principal Component Analysis. During the focus groups, each participant was allowed to express themselves freely without a time limit for their responses. Additionally, the interplay and discourse among the participants were meticulously observed, and the divergence of opinions concerning each inquiry was systematically analyzed.

4.5 Semi-structured interview

To obtain information from diverse perspectives of actors involved in the cocoa value chain, two semi-structured interviews were conducted with a technician and a manager. A semi-structured interview is a method of data collection that allows interviewees to provide detailed answers and specify the topics of their interest (Prazeres et al., 2022).

The initial interviewee was a cocoa value chain technician whose role involves visits to production units to advise smallholders on cocoa planting, harvesting, and processing. The second interviewee was a cocoa value chain manager whose function is to coordinate industrial activities and their links with the academic sector. Participants provided written consent for their involvement in the semi-structured interviews by signing an informed consent form. This form included a provision that authorized the recording and photographing of the activities.

The interview framework was supported by the results of the statistical analysis of the survey administered to 24 cocoa smallholders. The questions for each dimension were formulated to align with the variables prioritized in the Principal Component Analysis. During the interviews, each participant was allowed to express themselves freely without a time limit for their responses. Additionally, the graphic material used by the interviewees to explain their answers was meticulously observed, and the opinions concerning each inquiry were systematically analyzed.

4.6 Triangulation

The focus groups and semi-structured interviews were analyzed using the data triangulation technique, which leads to a holistic understanding of a phenomenon through the collection of information from different sources (Carter et al., 2014). The integration of primary and secondary sources, offering both coincident and dissenting quantitative and qualitative data, facilitated a comprehensive understanding of the dynamics of the cocoa value chain and the impact of agricultural activities on environmental, economic, and social sustainability.

The verification of the repeatability of an observation or interpretation, due to the convergence of sources, perceptions, and actors, is achieved by the triangulation process (Farquhar et al., 2020). This research employed a specific type of triangulation, the triangulation with an actor-based approach, which led to an analysis from the perspectives of cocoa smallholders, technicians, and managers. These perspectives were contrasted to determine the circular agriculture practice that impacts the sustainability of the cocoa value chain, and the action point to be implemented in the production units.

4.7 Product Analysis

The product analysis encompassed both chemical and economic analysis. The chemical analysis entailed a bromatological analysis of two samples of jam (see Figure 8). The first sample was derived from the mucilage of CCN-51 cocoa clone, while the second sample was derived from the mucilage of ICS-95 cocoa clone.

The selection of CCN-51 and ICS-95 varieties was predicted by their presence in all 24 production units and their representation of between 76% and 100% of the cocoa variety per crop. The production unit with the lowest percentage of CCN-51 and ICS-95 varieties was selected for the preparation of the cocoa mucilage jam. This selection was taken to determine the minimum profits that each smallholder would receive from the marketing of the jam.

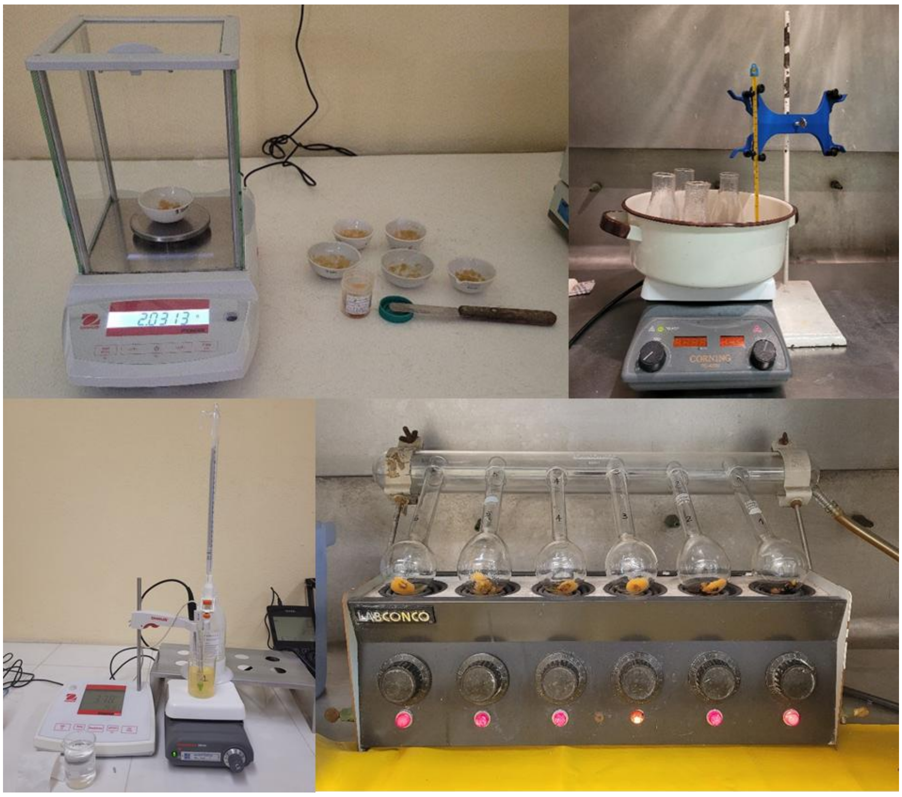

Figure 8. Bromatological analysis. Source: Own elaboration.

The bromatological analysis encompassed a series of seven tests, executed through micro-scale triplicate procedures. This methodological approach was employed to systematically compare and validate the results, ensuring the reliability and robustness of the findings:

1. Determination of acidity by volumetric method.
2. Determination of protein (raw) by the Microkjeldahl method.
3. Determination of humidity by the gravimetric method.
4. Determination of fat by the acid hydrolysis method.
5. Determination of ash by the gravimetric method.
6. Determination of total reducing sugars by the Fehling-Soxhlet method for glucose.
7. Determination of raw fibre (cellulose + hemicellulose) by the gravimetric method / modified Kennedy.

The economic analysis entailed the determination of the production costs of the food by-product, which represents the expenses incurred to generate the by-product. It also encompassed the potential annual income, which corresponds to the amount of income each smallholder would receive annually. Furthermore, the analysis included the profit margin, which shows the percentage of total revenue that becomes net profit after covering all costs and expenses.

4.8 Participatory mapping

A participatory mapping workshop was conducted with cocoa smallholders of the Otanche-San Pablo de Borbur-Pauna corridor to develop proposals for interaction between cocoa smallholders and their territory around the circular agriculture practices. The collaborative process of creating maps enables the participants of the participatory mapping to identify the relationships among local communities, places, and experiences (Logie et al., 2023).

The participatory mapping in the Otanche-San Pablo de Borbur-Pauna corridor (see Figure 9) included nine smallholders from Otanche (four women and five men), five people from San Pablo de Borbur (three women and two men), and seven participants from Pauna (seven women). Most of the smallholders were between the ages of 27 and 59, and they consented to participate in the participatory mapping workshop by signing an informed consent form. This form included a provision that authorized the recording and photographing of the activities.

Figure 9. Participatory mapping with cocoa smallholders. Source: Own elaboration.

The participatory mapping workshop was supported by the results of the statistical analysis of the survey administered to 24 cocoa smallholders. Each point and route of interaction between smallholders and their territory was assessed, incorporating both present and future scenarios that were aligned with the variables prioritized in the Principal Component Analysis. During the workshop, participants were permitted to articulate their scenarios without a time limit. Furthermore, the relationship among the participants was meticulously observed, and the individual and collective maps were systematically analyzed.

5. RESULTS

The RECOIN methodology was developed through three phases: Revision, Collection, and Interaction. These phases encompassed eight steps, whose results were illustrated in Figure 10. The implementation of both quantitative and qualitative research methodologies proved instrumental in conducting a comprehensive analysis of the impact of circular agriculture practices on the sustainability of the cocoa value chain within the department of Boyacá, Colombia.

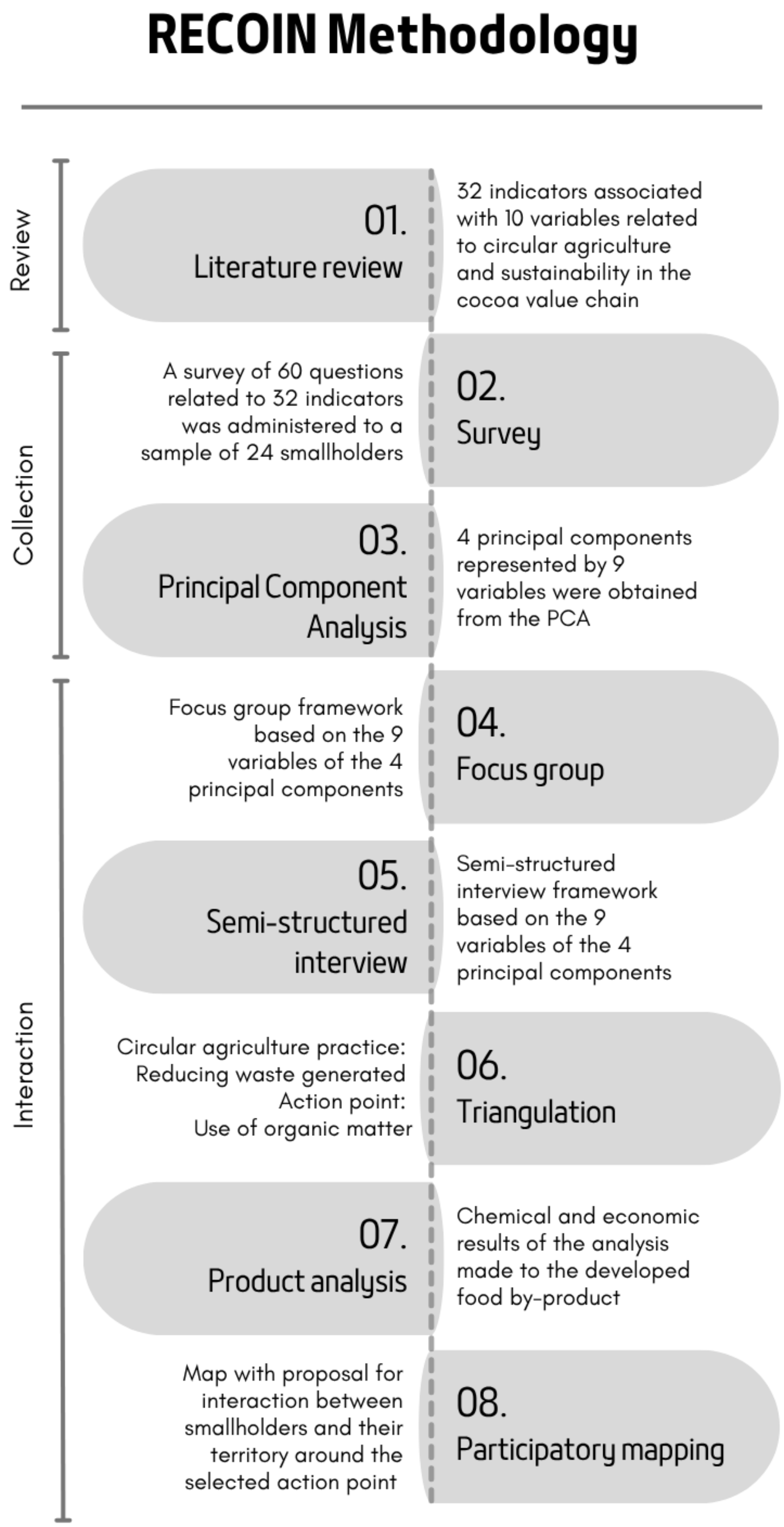

Figure 10. Results of the RECOIN methodology. Source: Own elaboration

The review phase was the initial phase of the study, which involved a literature review to identify the common variables and indicators between circular agriculture and sustainability in the cocoa value chain. The 80 articles under consideration yielded 31 common variables, of which 10 were selected due to the greatest recurrence and coincidence with the circular agriculture and sustainability items. These variables were associated with 32 indicators identified in the reviewed scientific articles.

The data collection phase incorporated the second and third steps. In the second step, a survey was administered to a sample of 24 cocoa smallholders from the Otanche-San Pablo de Borbur-Pauna corridor. The survey comprised 60 questions related to the 32 indicators identified in the previous phase. In the third step, the survey results were analyzed using the statistical technique of Principal Component Analysis. This analysis yielded four principal components represented by nine variables.

The interaction phase was comprised of the following five steps. The fourth and fifth steps entailed the execution of three focus groups and two semi-structured interviews, respectively. The focus group and interview framework were grounded in the nine variables of the four principal components that were identified in the preceding phase. The sixth step entailed a triangulation process to analyze the focus groups and the interviews. This triangulation process resulted in the selection of both the circular agriculture practice, reducing waste generated, and the action point, use of organic matter.

In the seventh step, a food by-product made of cocoa organic matter, namely, cocoa mucilage jam, was developed and analyzed from both a chemical and economic perspective. The chemical analysis revealed that the energy content of cocoa mucilage jam, which does not contain added sugar, is on average 275.73 kcal/100g, which is comparable to the energy content of commercial jams, which contain added sugar. The economic results demonstrate that the profit margin of the cocoa mucilage jam is 27%, and the potential income from jam sales is equivalent to 24% of the income from cocoa bean sales received.

The eighth step entailed a participatory mapping with cocoa smallholders of the Otanche-San Pablo de Borbur-Pauna corridor. The result was a map delineating a proposed marketing strategy grounded on four potential agrotourism routes. A selection of four production units was made by smallholders, who identified those with the greatest potential for agrotourism. The selection included one production unit in the municipality of Pauna, one in San Pablo de Borbur, and two in the municipality of Otanche.

5.1 Literature review

The literature review was conducted using 80 scientific articles, which yielded 31 common variables between circular agriculture practices and sustainability. These variables were classified according to the dimensions of sustainability (environmental, economic, and social), as well as to the percentage of recurrence in the selected scientific articles.

The environmental dimension comprised 11 variables, 4 of which exhibited the highest recurrence: Soil, Fertilizers and pesticides, Water, and Waste, which was also associated with the term "biomass generated". The economic dimension comprised 12 variables, 3 of which occurred with the highest recurrence: Income, Biomass valorization, and Marketing, which was also associated with the term "networks". The social dimension comprised 8 variables, 3 of which exhibited the highest recurrence: Knowledge, Associativity (it was also associated with the term "community organization"), and Institutional (it was also associated with the term "government support"), as shown in Table 4.

Table 4. Variables associated with circular agriculture and sustainability. Source: Own elaboration.

Dimension	Variable	Sustainability	Circular agriculture
Environmental	Soil	76%	100%
	Fertilizers and pesticides	59%	86%
	Water	88%	100%
	Waste (biomass generated)	53%	77%
	Agricultural biodiversity	26%	14%
	Energy	47%	45%
	Flora and fauna	33%	32%
	Air	33%	9%
	Climate	41%	36%
	Agroforestry system	26%	55%
	Pest control	5%	45%
Economic	Income	88%	86%
	Marketing (networks)	74%	68%
	Biomass valorization	66%	91%
	Expenses	12%	36%
	Productivity	41%	23%
	Returns	34%	32%
	Product quality	3%	32%
	Transport	16%	9%
	Added value	3%	36%
	Market	45%	23%
	Income diversification	3%	14%
	Access to bank loans	29%	9%
Social	Associativity (community organization)	88%	64%
	Knowledge	97%	68%
	Institutional (government support)	79%	55%
	Technologies	38%	36%
	Land	47%	23%
	Quality of life	26%	9%
	Education	50%	36%
	Cultural practices (crop management)	5%	45%

Recurrence greater than 50% Recurrence between 30% and 50% Recurrence less than 30%

Of the 31 variables, 10 were selected because they demonstrated a recurrence greater than 50% and coincidence between the circular agriculture and sustainability items. The 10 variables were associated with 32 indicators identified in the scientific articles reviewed. The environmental dimension included 4 variables associated with 12 indicators; the economic dimension integrated 3 variables related to 9 indicators; and the social dimension consisted of 3 variables associated with 11 indicators, as illustrated in Table 5.

Table 5. List of indicators associated with variables for each dimension. Source: Own elaboration.

Dimension	Variable	Indicator
Environmental	Soil	Agroforestry_system
		Associated_crop
		Crop_yield
		Annual_production
		Animals_number
		Animal_manure
	Fertilizers and pesticides	Pesticide_use
		Biological_control
		Chemical_fertilizer
		Organic_fertilizer
	Water	Irrigation_system
	Waste (biomass generated)	Production_losses
Economic	Income	Daily_wage
		Cocoa_sales
		Monthly_expenses
		Economic_losses
		Lossmin_plan
	Marketing (networks)	Certification_processes
		Cocoa_trade
	Biomass valorization	Cocoawaste_reuse
		Pruningwaste_reuse
Social	Associativity (community organization)	Association_Membership
		Hectare_PU
		Trees_PU
		Family_members
		Workers_PU
		Working_days
	Knowledge	Technology_access
		Resourcereuse_PU
	Institutional (government support)	Property_PU
		Government_participation
		Crop_substitution

The indicators indicated a growing approach to circular agriculture from a sustainability perspective, as well as a strong correlation between the environmental, economic, and social dimensions. It is noteworthy that the associated scientific articles addressed recurring themes, including the utilization of fertilizers and access to natural resources, as well as the exploration of innovative subjects such as the implementation of new technologies and material flow management.

5.2 Survey

The survey was developed based on the dimensions, variables, and indicators identified in the literature review (see Table 5). The survey contained a total of 60 questions (see Annex 1). Of these, 25 pertained to the environmental dimension, 13 to the economic dimension, and 15 to the social dimension. The remaining 7 questions gathered basic information on each cocoa production unit, enabling the characterization of smallholders by age groups, gender distribution, education level, and access to public utilities.

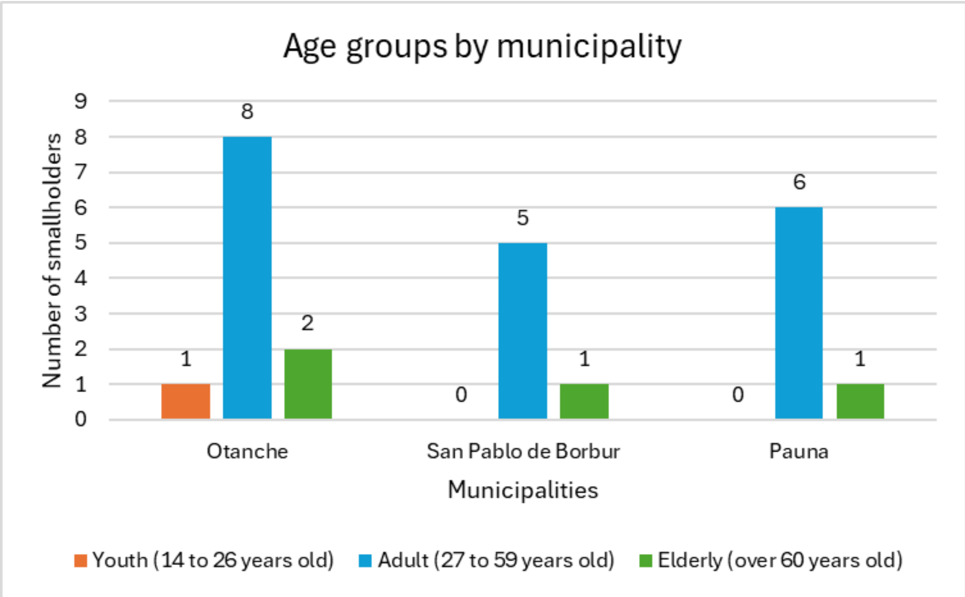

Figure 11. Age groups by municipality. Source: Own elaboration.

Most smallholders were between 27 and 59 years old, suggesting that the corridor possesses the productive capacity to sustain cocoa crops. Nonetheless, the fact that there was only one smallholder in the youth age group is of concern. The generational relay is guaranteed by the participation of young people in the daily routine of cocoa cultivation. This phenomenon aligns with the findings of prior research conducted in Colombia, which revealed that the average age of cocoa producers ranges from 54 to 56 years, indicating a limited engagement of young people (Vargas et al., 2023). The presence of elderly individuals within each municipality fosters the transfer of knowledge to younger producers, thereby facilitating the continuity of agricultural expertise.

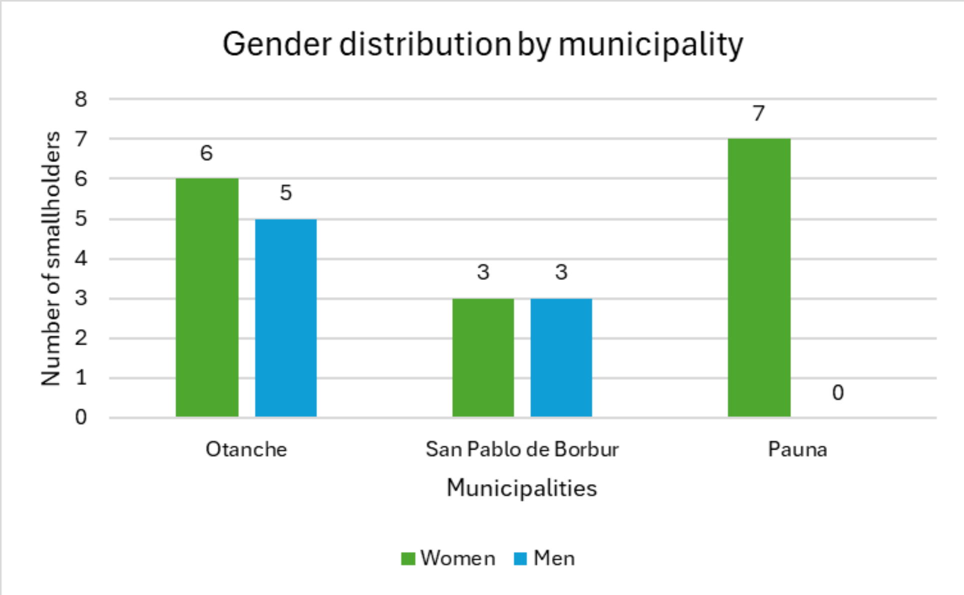

Figure 12. Gender distribution by municipality. Source: Own elaboration.

The gender distribution by municipality demonstrated an increasing participation of women in the technical and managerial aspects of cocoa cultivation. This phenomenon is noteworthy, as research conducted in Colombia, as evidenced by Vargas et al. (2023), it has been demonstrated that 72.7% of cocoa producers are male. Regarding the implementation of circular agricultural practices, the findings of field research indicate that 66.6% of smallholders engaging in these practices are female.

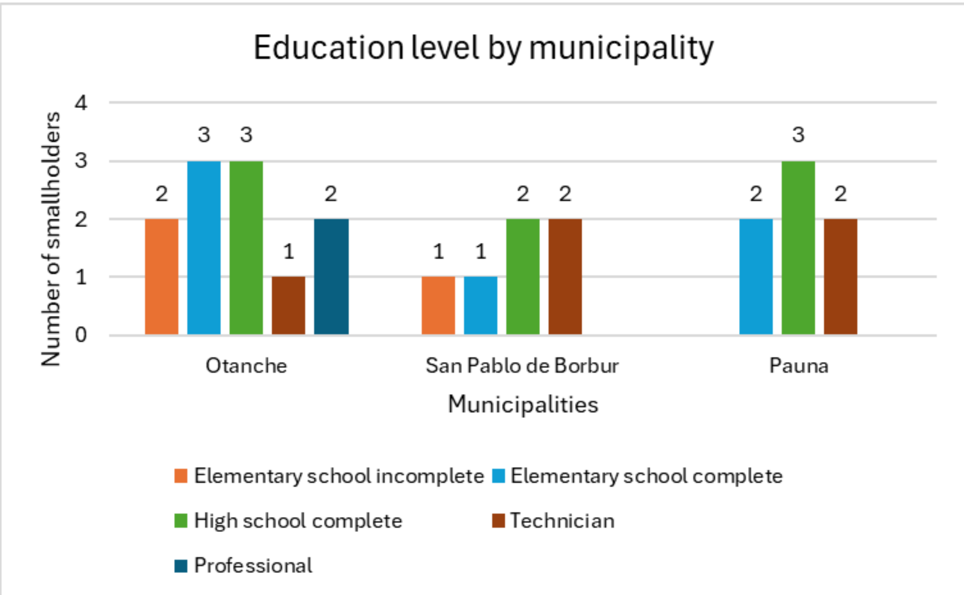

Figure 13. Education level by municipality. Source: Own elaboration.

The characterization of the educational level indicated that 62.5% of the smallholders completed their basic academic training. Of the 24 participants, only two managed to reach a professional academic level. Of the five smallholders who have received technical training, only one has received training related to the agricultural sector. The remaining respondents have received training for administrative positions within the city. This phenomenon has garnered the attention of new generations, who are increasingly migrating to urban areas.

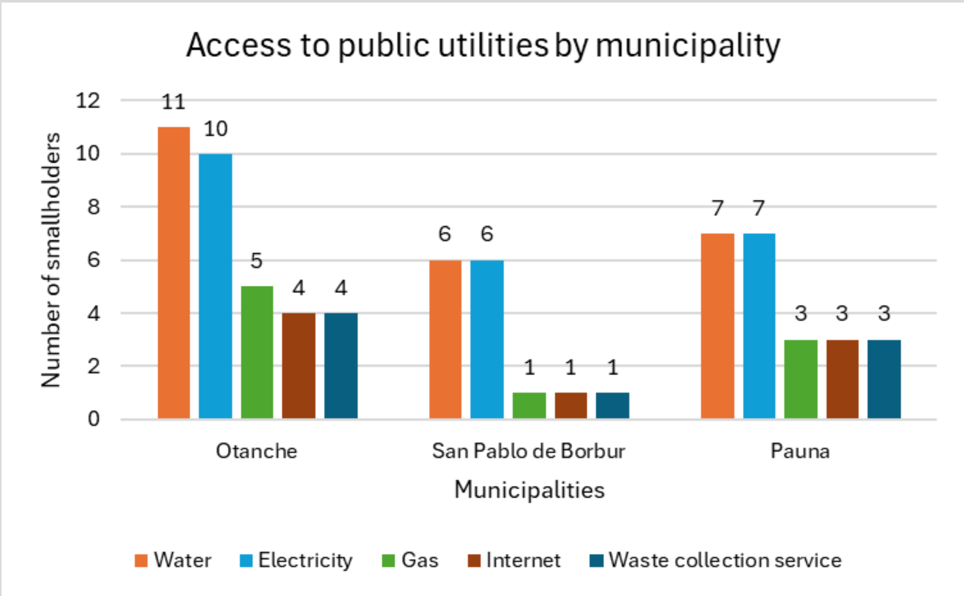

Figure 14. Access to public utilities by municipality. Source: Own elaboration.

The findings of this research have indicated a scarcity of access to public utilities, including gas, internet, and waste collection in the Otanche-San Pablo de Borbur-Pauna corridor. Of particular concern is the practice of combining domestic waste with crop waste for stacking in production units, as observed through field research. This combination may potentially result in the generation of vectors capable of affecting human health. The involvement of local authorities in ensuring waste collection in production units is imperative. Furthermore, educational programs are necessary to modify the cultural practices of waste management in the production units.

5.3 Principal Component Analysis

The Principal Component Analysis (PCA) was based on the results of the survey applied to 24 cocoa smallholders. The data were statistically analyzed through the Shapiro-Wilk normality test, the Spearman correlation coefficient, and Principal

Component Analysis, with R software serving as the statistical analysis software. This technique enabled the selection of the environmental, economic, and social variables that offered the most substantial information to the model and the Principal Components assembly. The latter explained the link between circular agriculture and sustainability in the cocoa value chain.

The Shapiro-Wilk normality test indicated that, in each of the environmental, economic, and social dimensions, the data did not have a normal distribution. These results were then used as inputs for the execution of the correlation analysis through the Spearman method. After the implementation of this method in R software, a correlation matrix was obtained for each of the dimensions of sustainability: environmental, economic, and social, as illustrated in Figures 15, 16, and 17, respectively.

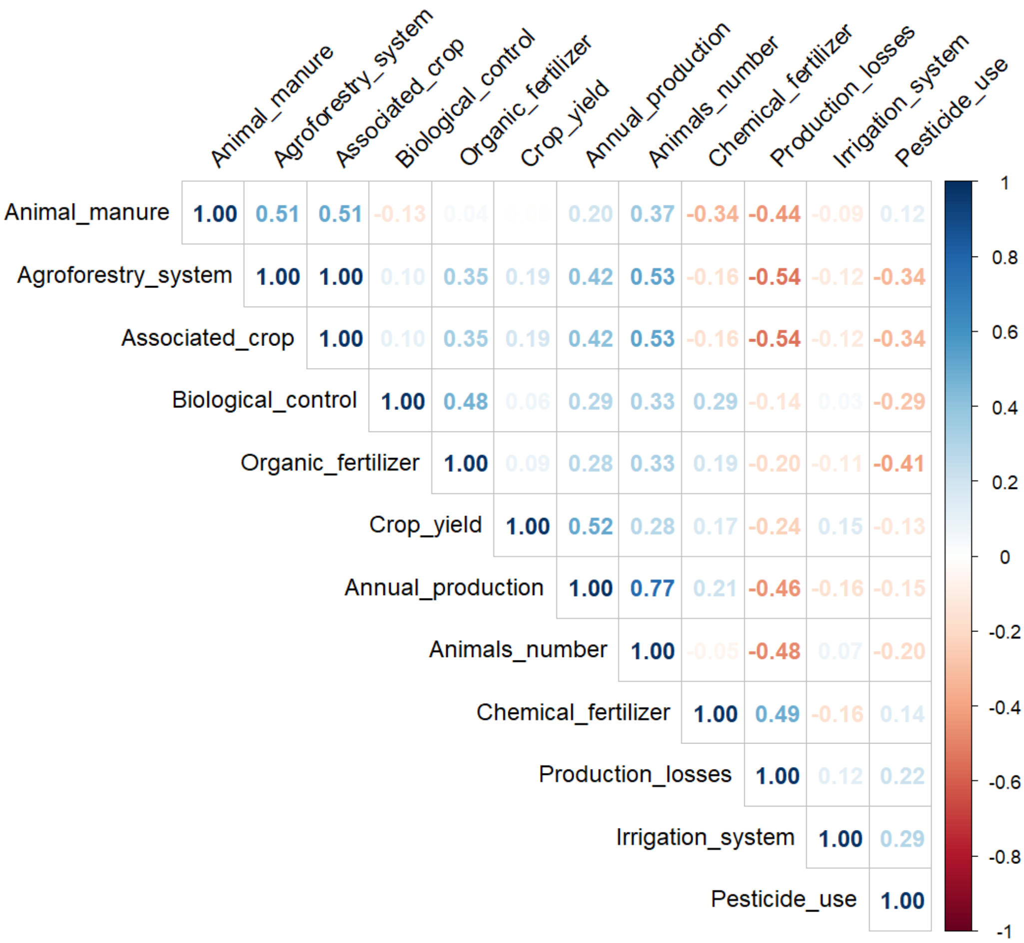

Figure 15. Correlation matrix of the environmental dimension. Source: Own elaboration using R software.

The degree of association between the 12 variables that comprised the environmental dimension indicated that 6 variables met the correlation criteria. These 6 variables were selected to carry out the Principal Component Analysis. The variables were: Agroforestry_system, Annual_production, Animals_number, Organic_fertilizer, Irrigation_system, and Production_losses.

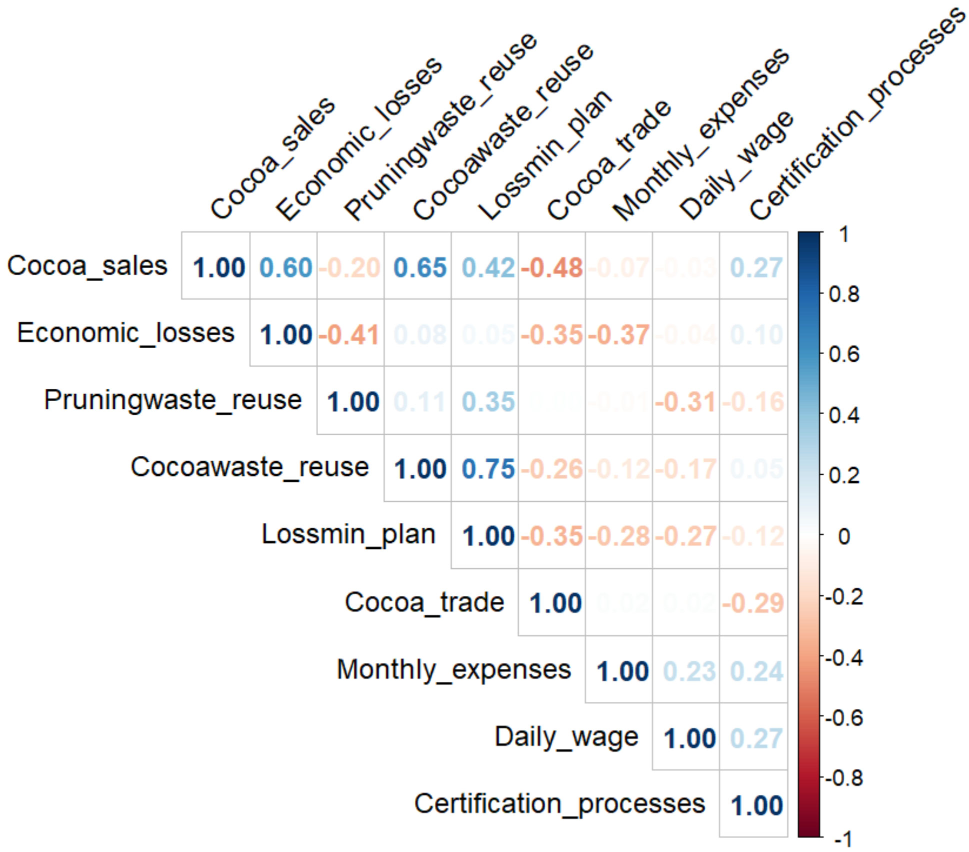

Figure 16. Correlation matrix of the economic dimension. Source: Own elaboration using R software.

The degree of association between the 9 variables that comprised the economic dimension indicated that 4 variables met the correlation criteria. These 4 variables were selected to carry out the Principal Component Analysis. The variables were: Cocoa_sales, Economic_losses, Cocoa_trade, and Cocoawaste_reuse.

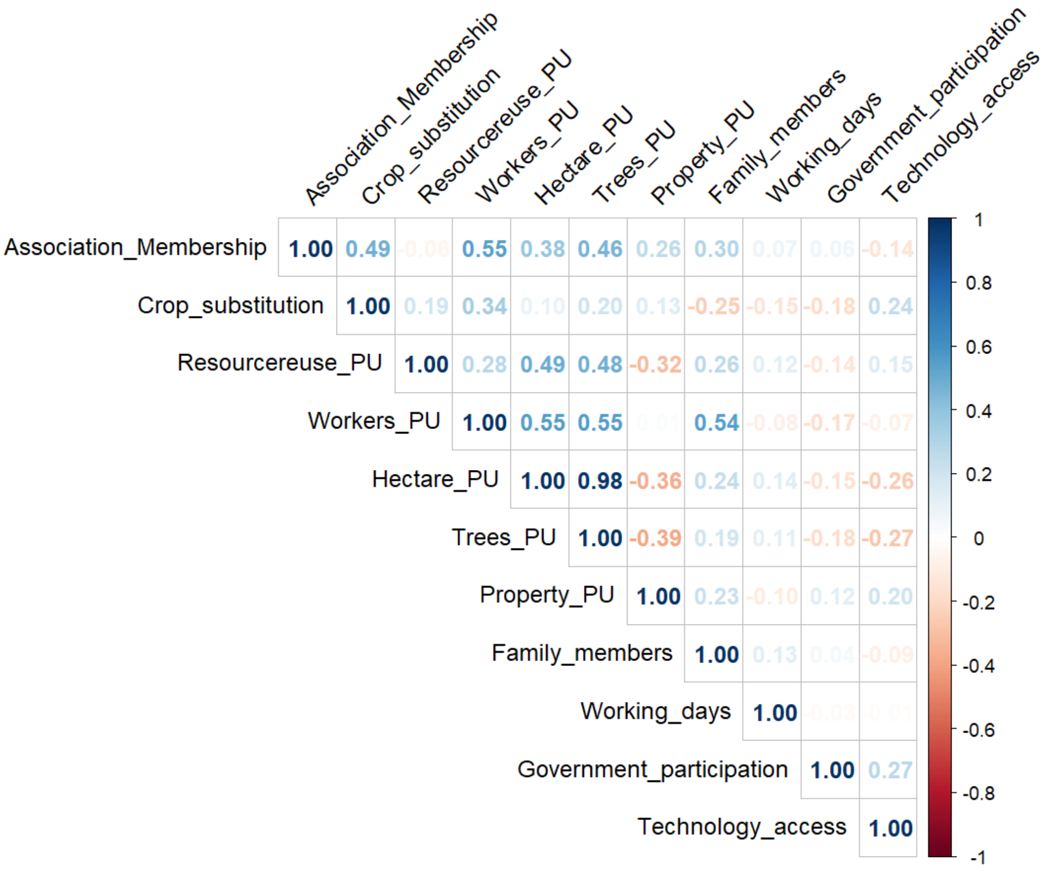

Figure 17. Correlation matrix of the social dimension. Source: Own elaboration using R software.

The degree of association between the 11 variables that comprised the social dimension indicated that 5 variables met the correlation criteria. These 5 variables were selected to carry out the Principal Component Analysis. The variables were: Association_Membership, Hectare_PU, Workers_PU, Resourcereuse_PU, and Crop_substitution.

The Principal Component Analysis was executed with the 15 selected variables: 6 variables from the environmental dimension, 4 from the economic dimension, and 5 from the social dimension. The significance of the Principal Components (PC) demonstrated that PC1, PC2, PC3, and PC4 explained 75.1% of the variance in the data, with a standard deviation greater than 1 (see Table 6).

Table 6. Significance of the Principal Components (PC). Source: Own elaboration using R software.

	PC1	PC2	PC3	PC4	PC5
Standard deviation	2.5234	1.4389	1.2593	1.11052	0.9518
Proportion of Variance	0.4245	0.1380	0.1057	0.08222	0.0604
Cumulative Proportion	0.4245	0.5625	0.6683	0.75048	0.8109

	PC6	PC7	PC8	PC9	PC10
Standard deviation	0.90058	0.76439	0.69759	0.60581	0.53208
Proportion of Variance	0.05407	0.03895	0.03244	0.02447	0.01887
Cumulative Proportion	0.86495	0.90390	0.93634	0.96081	0.97968

	PC11	PC12	PC13	PC14	PC15
Standard deviation	0.40044	0.26351	0.21597	0.16533	0.03166
Proportion of Variance	0.01069	0.00463	0.00311	0.00182	0.00007
Cumulative Proportion	0.99037	0.99500	0.99811	0.99993	1.00000

The proportion of variance explained by each component indicated that PC1 had the maximum proportion with 42.5%, indicating that this Principal Component captured the largest percentage of information from the original data set. PC2 occupied the second position with 13.8%. The third place was taken by PC3 with 10.6%, and PC4 represented 8.2%.

The correlation between PC1 and PC2, PC2 and PC3, PC3 and PC4 was explained through biplots, which were run in R software with a confidence level of 0.95. These biplots, graphical representations, considered both the direction and magnitude of vectors to determine the significance of each variable in each component, as shown in Figures 18, 19, and 20, respectively.

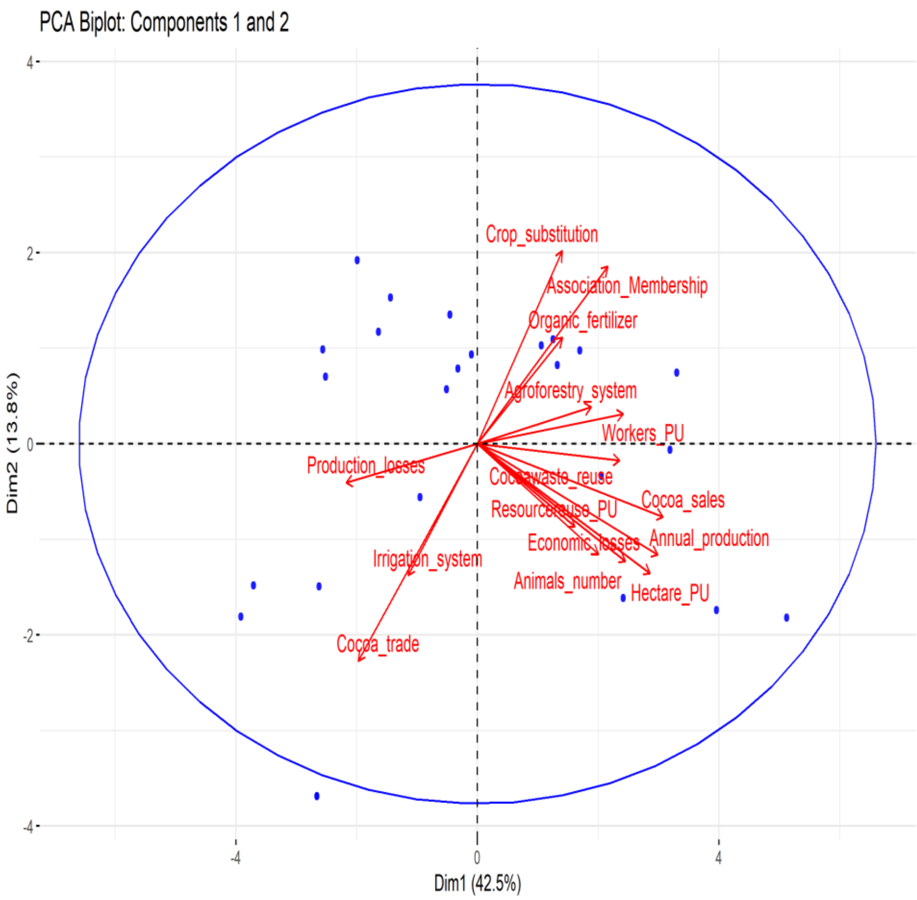

Figure 18. Biplot of Principal Components 1 and 2. Source: Own elaboration using R software.

The length and direction of the variable vectors represented in the biplot of Principal Components 1 and 2 indicated that the following variables in the environmental, economic, and social dimensions demonstrated the strongest correlation with PC1 and PC2:

- Environmental dimension: Annual_production
- Economic dimension: Cocoa_sales, Cocoa_trade
- Social dimension: Association_Membership, Hectare_PU

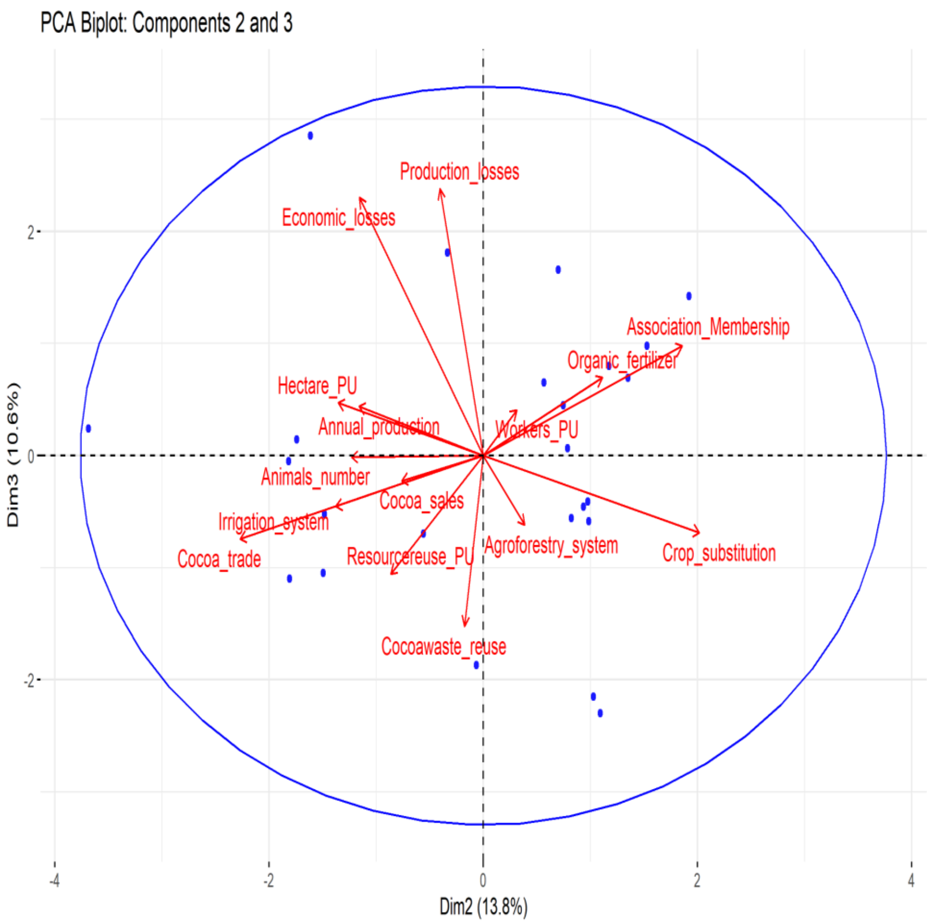

Figure 19. Biplot of Principal Components 2 and 3. Source: Own elaboration using R software.

The length and direction of the variable vectors represented in the biplot of Principal Components 2 and 3 indicated that the following variables in the environmental, economic, and social dimensions demonstrated the strongest correlation with PC2 and PC3:

- Environmental dimension: Production_losses
- Economic dimension: Economic_losses, Cocoa_trade
- Social dimension: Association_Membership

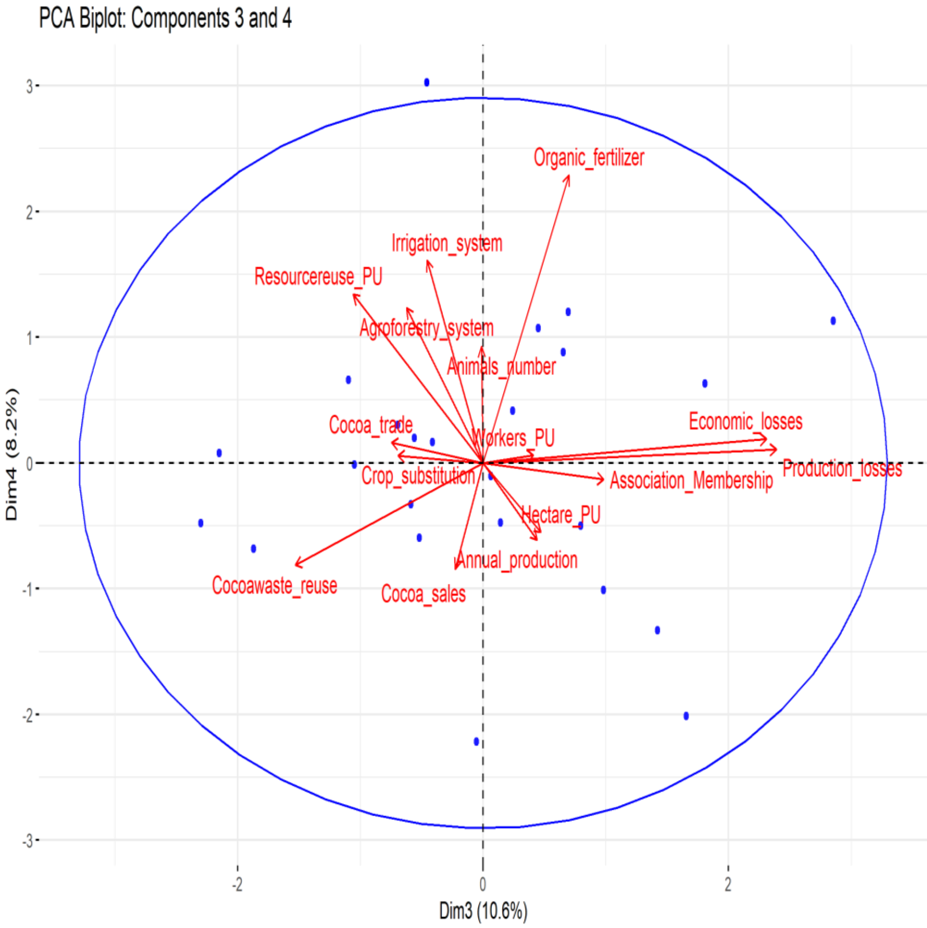

Figure 20. Biplot of Principal Components 3 and 4. Source: Own elaboration using R software.

The length and direction of the variable vectors represented in the biplot of Principal Components 3 and 4 indicated that the following variables in the environmental and economic dimensions demonstrated the strongest correlation with PC3 and PC4:

- Environmental dimension: Organic_fertilizer, Production_losses
- Economic dimension: Economic_losses, Cocoawaste_reuse

The Principal Component Analysis indicated that nine variables demonstrated the strongest correlation with the four Principal Components, which explained 75.1% of the variance in the data. The distribution of these variables follows the dimensions of sustainability:

- Environmental dimension: Annual_production, Organic_fertilizer, Production_losses.
- Economic dimension: Cocoa_sales, Economic_losses, Cocoa_trade, Cocoawaste_reuse.
- Social dimension: Association_Membership, Hectare_PU.

5.4 Focus group

The focus group framework (see Annex 2) was based on the nine variables prioritized by the Principal Component Analysis. A focus group was conducted for each of the municipalities of the Otanche-San Pablo de Borbur-Pauna corridor. The responses of each participant in the focus group were transcribed and analyzed using ATLAS.ti software, which facilitated the management of text-based data. The categories and codes that emerged from the research were linked to each other through circuits.

In the context of the environmental dimension, the variables Annual_production, Organic_fertilizer, and Production_losses, served as the foundation for the development of speeches by smallholders. The content of these speeches was focused on the categories of organic cultivation, proper use of fertilizers, and pest control alternatives (see Figure 21).

In the economic dimension, the variables Cocoa_sales, Economic_losses, Cocoa_trade, and Cocoawaste_reuse were involved. A consensus emerged among the smallholders that the most pertinent category pertains to the utilization of cocoa waste. In the social dimension, with the associated variables Association_Membership and Hectare_PU, smallholders focused on the categories of smallholder associations and community meetings (see Figure 21).

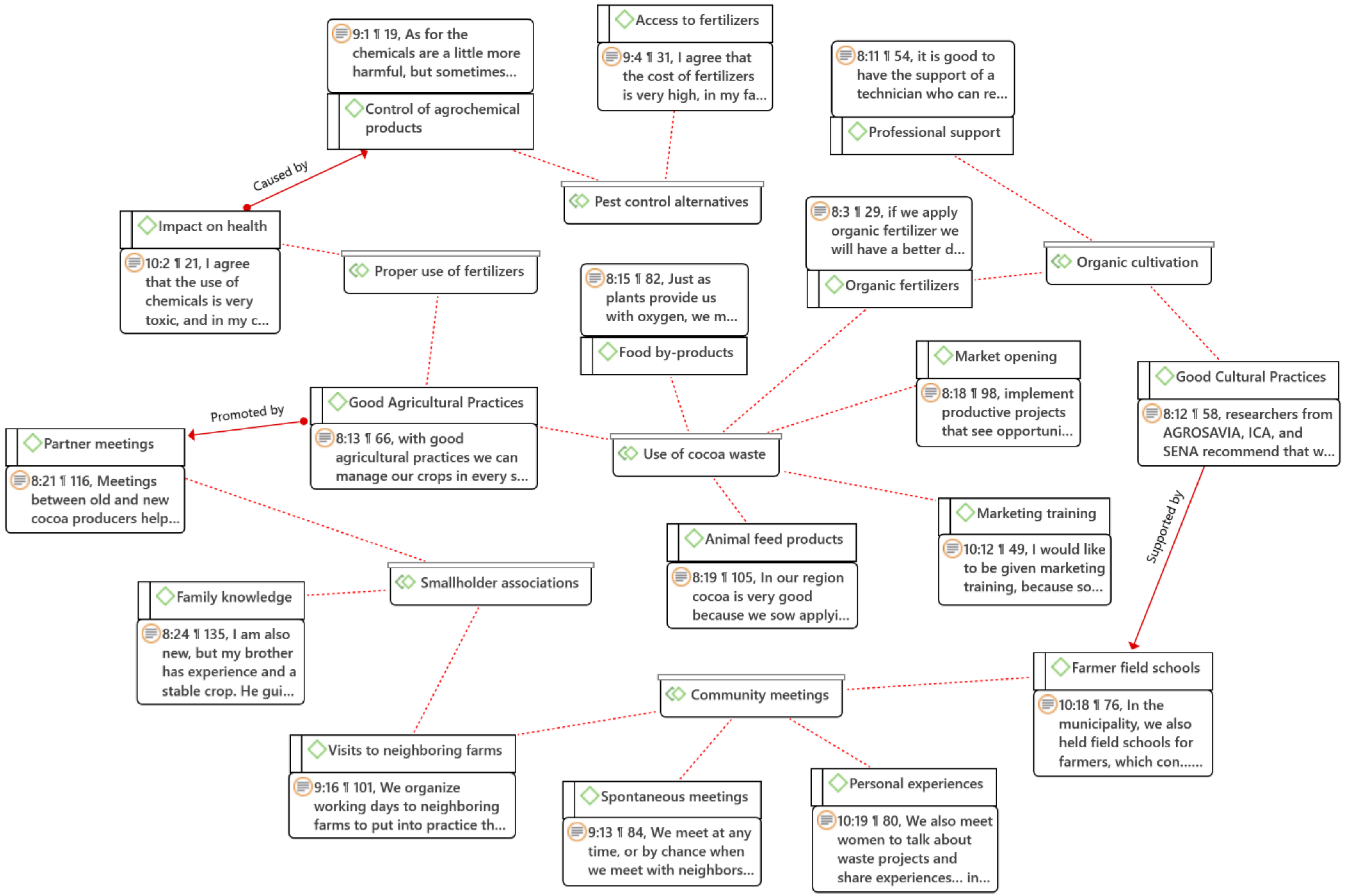

Figure 21. Network map associated with the focus groups of the Otanche-San Pablo de Borbur-Pauna corridor. Source: Own elaboration using ATLAS.ti software.

The network map demonstrated that smallholders have been and continue to be engaged in the transition from chemical fertilizers to organic fertilizers. This shift is driven by the awareness among smallholders of the deleterious environmental consequences of chemical fertilizers. As stated by the smallholder Jose Real from the Otanche municipality, *“If we use cypermethrin or regent we are destroying the biodiversity of the crop, such as pollinating mosquitoes, which help us to have a very good harvest; we are destroying the soil microorganisms that facilitate the decomposition of organic matter, essential for plant absorption”.*

Smallholders pointed out that the persistent use of chemical fertilizers exerts a detrimental influence on both the environment and human health. In the three focus groups, several participants mentioned negative experiences with the recurrent use of agrochemicals, which increased their production but affected their health. For instance, the smallholder Jose Torres from the San Pablo de Borbur municipality stated, *“I agree that the use of chemicals is very toxic, and in my case, I'm the fumigator. I don't like the use of chemical fertilizers because they affect my health”.*

For all smallholders, the most effective circular agriculture practice within the cocoa value chain was the reduction of waste generated. The utilization of this organic matter has been identified as a critical action point for fostering the development of marketable products. This assertion was corroborated by the smallholder Diana Martinez from the Otanche municipality, who asserted, *“Just as plants provide us with oxygen, we must support them in generating a clean environment, for example, the transformation of food derived from what has been considered waste is a good way to support the environment, and that also generates money for us”*.

Associativity constitutes a pivotal component of cocoa cultivation, serving as a conduit for the dissemination of knowledge and experiences among smallholders. Cases of success and failure around the transformation of cocoa waste have been disseminated among smallholders during spontaneous meetings and through practical experiences during site visits to neighboring farms. As stated by the smallholder Flor Torres from the Pauna municipality, *“I encourage my colleagues to partake in training courses and apply their knowledge, for example, I did not know how to do pruning, but I sought guidance at a neighboring farm, where I was instructed, and now I know how to prune”*.

5.5 Semi-structured interview

The interview framework (see Annex 3) was based on the nine variables prioritized by the Principal Component Analysis. Two semi-structured interviews were conducted with a technician and a manager of the cocoa value chain. The responses of each participant in the interview were transcribed and analyzed using ATLAS.ti software, which facilitated the management of text-based data. The categories and codes that emerged from the research were linked to each other through circuits.

5.5.1 Technician interview

Regarding the environmental dimension and its associated variables Annual_production, Organic_fertilizer, and Production_losses, the technician formulated his responses according to the category of proper use of fertilizers. In the economic dimension, the variables of Cocoa_sales, Economic_losses, Cocoa_trade, and Cocoawaste_reuse were incorporated into the technical speech, which was centered on the use of cocoa waste. About the social dimension and its associated variables Association_Membership and Hectare_PU, the technician's focus was on the category of smallholder associations (see Figure 22).

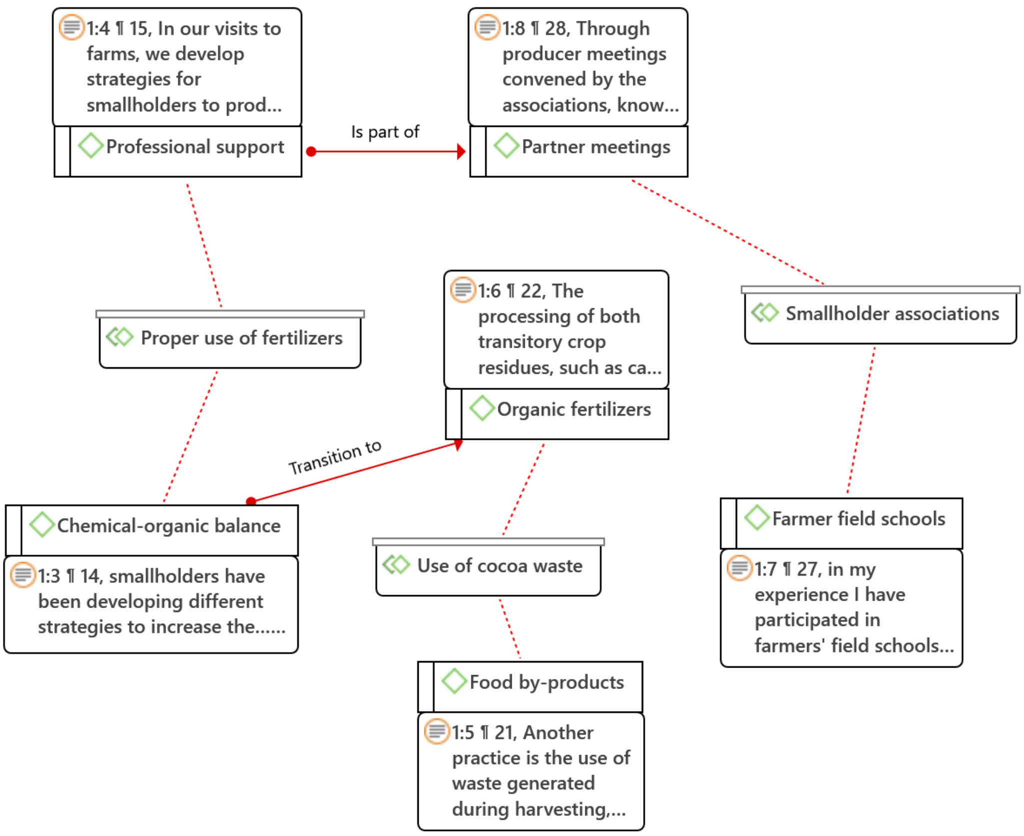

Figure 22. Network map associated with the semi-structured interview for a technician. Source: Own elaboration using ATLAS.ti software.

The network map demonstrated that, from a technical point of view, cocoa crops in the Boyacá region have increased the implementation of Good Agricultural Practices (GAP). GAP entails a balanced use of chemical and organic fertilizers, with a tendency towards predominantly organic management. This has improved the quality of the harvest and enabled smallholders to be more competitive in the market. The technician pointed out that the adoption of GAP is possible with professional technical support, which is based on the provision of ongoing accompaniment and advice to smallholders to carry out their productive initiatives, such as the development of organic fertilizers with cocoa waste in their production units.

The analysis conducted by the technician indicated that the most viable circular agriculture practice to be implemented in the cocoa value chain is the reduction of waste using organic matter generated. This activity enables the efficient management of waste in each production unit and generates income for smallholders. As the technician stated, *“Another practice is the use of waste generated during harvesting, because the producer focuses only on what currently generates income, seeds. However, we have identified individual initiatives that use waste to produce food and beverages”.*

From a technical perspective, partner meetings constituted the most significant mechanism for the dissemination of knowledge and the promotion of awareness among producers regarding the various initiatives that were developed, both individually and collectively, in production units to process cocoa waste. These meetings are attended by smallholders, who possess the relevant experience, and technicians, who complement the knowledge of smallholders from a technical perspective.

5.5.2 Manager interview

The interview conducted with a manager of the cocoa value chain revealed that significant progress has been made in the environmental dimension, particularly regarding the transition from illegal to legal cultivation. In the economic dimension, the category of use of cocoa waste was the one that included the most developments and advances in research. Concerning the social dimension, the manager's presentation focused on the development of concepts about the category of smallholder associations (see Figure 23).

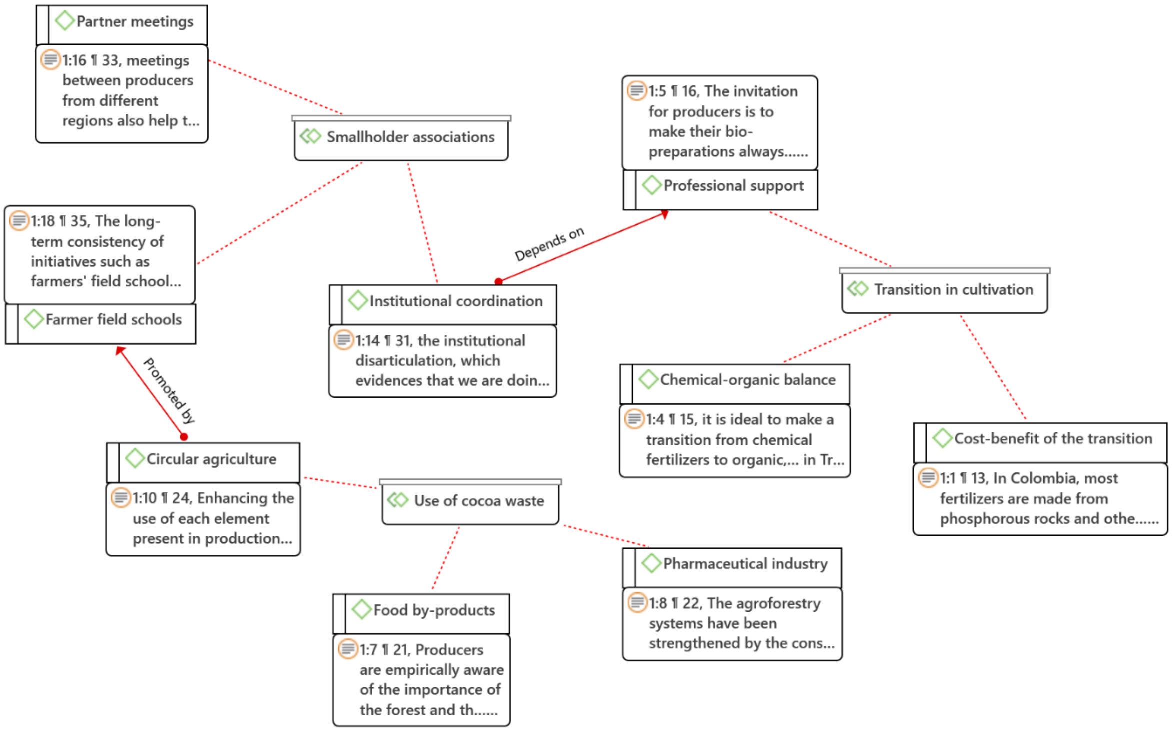

Figure 23. Network map associated with the semi-structured interview for a manager. Source: Own elaboration using ATLAS.ti software.

The network map illustrated that, from a managerial perspective, cocoa cultivation in Colombia is undergoing a transition towards organic cultivation. Regions such as Boyacá have demonstrated progress in the utilization of organic fertilization. The cost-benefit implications of this transition present a challenge for managers, who must collaborate with smallholders to encourage greater emphasis on quality over quantity in their harvests. Furthermore, the manager pointed out that this transition is time-consuming and requires consistency and collaboration between smallholders, technicians, and managers.

The analysis conducted by the manager indicated that the circular agriculture practice that best suits the conditions of the cocoa value chain in Colombia is the reduction of waste, which is linked to the use of organic matter generated during agricultural activities. The cocoa organic matter has demonstrated potential applications in the food, pharmaceutical, and cosmetic industries. As stated by the manager, *"Processes for waste management also contribute to the well-being of communities, for example, the transformation of cocoa pod husk into organic fertilizers, and the transformation of mucilage into food by-products and herbicides"*.

The implementation of circular agriculture practices is supported by the dissemination of knowledge and experiences among smallholders. The manager indicated that farmer field schools, partner meetings, and association meetings are instrumental in this process. The exchange of information must be accompanied by representatives of public and private institutions, who must coordinate with one another to avoid redundant efforts. As the manager stated, *"The institutional disarticulation, which evidences that we are doing the same research and processes in different institutions, just with different names, generates disinterest in the producers"*.

5.6 Triangulation

The contrast of focus groups and semi-structured interviews demonstrated that there is an increased transition to organic cocoa cultivation in agroforestry systems. Smallholders indicated a clear preference for the utilization of organic fertilizers and the implementation of Good Cultural Practices, which are associated with crop management. Additionally, Good Agricultural Practices, which are related to cocoa production, were identified as a key area of concern. 79% of the smallholders who participated in the research developed cultivation in agroforestry systems, and 29% certified their production units in Good Agricultural Practices by the Colombian Agricultural Institute.

Despite a consensus among smallholders, technicians, and managers that the utilization of organic fertilizers should be prioritized in cacao crops, given their environmental benefits and the potential for enhancing the long-term economic viability of stakeholders within the cocoa value chain, participants underscored the challenges associated with maintaining pest control through exclusively organic methods, citing the instance of pests such as the carmenta *(Carmenta foraseminis)* and the leaf-cutting ant *(Atta cephalotes)*.

Diseases such as frosty pod rot *(Moniliophthora roreri)* and witches' broom *(Moniliophthora perniciosa)* have been observed to respond to a chemical-organic balance treatment strategy. This approach involved the use of chemicals only when pests or diseases required intervention, complemented by the consistent application of organic fertilizers throughout the year.

The three actors reached a consensus that the practice of waste reduction using organic matter is the most suitable for the agricultural processes of the cocoa value chain. This conclusion was informed by data provided by smallholders, which indicated that the annual generation of cocoa pod husk and mucilage in each production unit averages 3,514 kg/ha. This organic matter is classified as waste and stacked in the production unit. This amount is up to eight times greater than the production of dry beans, and this is because, according to measurements made by Torres (2023), the bean or seed represents between 21 and 23% of the cocoa pod, while about 80% is made up of the other components (see Figure 24).

Figure 24. Cocoa pod composition. Source: Own elaboration based on Torres, 2023.

Smallholders have developed empirical projects to utilize organic matter that constitutes 80% of cocoa pods, which is currently discarded as waste. Among these materials, the cocoa pod husk emerged as a notable component, finding application in the production of organic fertilizers and handicrafts. The mucilage or pulp, meanwhile, was utilized in the fabrication of jams and whiskey, while the bean shell or testa was employed in the preparation of cookies. All participants in the research identified jam as the product with the greatest potential for marketing since it requires less time and economic investment for its elaboration.

Most of the new products in the cocoa value chain of the Otanche-San Pablo de Borbur-Pauna corridor have been developed through individual processes, that is, in the production unit of each smallholder. However, the results have been socialized with partners through various channels, including associations and community meetings, both planned and spontaneous. Knowledge management was identified as a critical point to strengthen associativity, disseminate findings, and develop alternative markets.

5.7 Product Analysis

The action point concerning the use of organic matter focused on the potential marketing of a food by-product, namely, jam made of cocoa mucilage from CCN-51 and ICS-95 cocoa clones. The selection of these clones was predicated on their presence in all 24 production units and their representation of between 76% and 100% of the cocoa variety per crop in the Otanche-San Pablo de Borbur-Pauna corridor.

5.7.1 Chemical analysis

To determine the chemical and nutritional composition of cocoa mucilage jam, the production unit "La Soledad" was selected. This unit is located in the "Buzal" neighborhood of the Otanche municipality. This unit was chosen due to its status as the production unit with the lowest percentage of CCN-51 and ICS-95 varieties.

In 2024, "La Soledad" generated 2,636 kg/ha of cocoa pod husk and mucilage, of which 791 kg (30%) were of CCN-51, 1,212 kg (46%) were of ICS-95, and 633 kg (24%) were of other varieties. The production process entailed the manual harvesting, opening, and shelling of the cocoa pods. The extraction of the mucilage juice was carried out using a manual press, and the resultant mixture was cooked until achieving a consistency resembling jam, as illustrated in Figure 25.

Figure 25. Cocoa mucilage jam production process. Source: Own elaboration.

The data concerning the production process of the cocoa mucilage jam were calculated to yield 0.25 kg of by-product, which is the most marketed presentation in Colombia. The variables of cocoa pod husk and mucilage, collection time of mucilage juice, volume of extracted mucilage juice, and cooking time of mucilage juice were measured for CCN-51 and ICS-95 clone varieties, as shown in Table 7.

Table 7. Data of the jam production process. Source: Own elaboration.

Sample	Clone variety	Cocoa pod husk and mucilage (kg)	Collection time of mucilage juice (s)	Volume of extracted mucilage juice (l)	Cooking time of mucilage juice (s)	Cocoa mucilage jam (kg)
1	CCN-51	8.16	2,096	1.18	1,806	0.25
2	ICS-95	10.34	2,186	1.41	1,590	0.25

The results of the bromatological analysis revealed the chemical and nutritional composition of cocoa mucilage jam. This composition was determined by measuring the pH, moisture, protein, fat, total carbohydrates, total solids, ash, acidity, fiber, and energy levels of the samples, as shown in Table 8.

Table 8. Composition of cocoa mucilage jam. Source: Own elaboration.

Parameter	Clone variety	
	CCN-51	ICS-95
pH	3.08	3.25
Moisture (%)	31.14	37.15
Protein (%)	2.58	2.26
Fat (%)	3.64	2.79
Total carbohydrates (%)	61.86	56.70
Total solids (%)	68.86	62.85
Ash (%)	1.40	1.12
Acidity (%)	4.49	3.13
Fiber (%)	-	-
Energy (kcal/100 g)	290.53	260.92

The composition parameters that were analyzed demonstrated that the jams of the two clone varieties possess a satisfactory nutritional content, with higher values of specific parameters such as protein and fat in comparison to commercial jams. This nutritional content was verified by comparing the average of the results obtained for the two clone varieties, and the average of four samples of commercial jam, obtained from research carried out by Mohd Naeem et al. (2017) about the nutritional composition of fruit jams in the Malaysian market (see Table 9).

Table 9. Comparison between cocoa mucilage jam and commercial jam. Source: Own elaboration with elements of Mohd Naeem et al. (2017).

Parameter	Cocoa mucilage jam	Commercial jam
Moisture (%)	34.14	31.98
Protein (%)	2.42	0.36
Fat (%)	3.21	0.02
Total carbohydrates (%)	59.28	67.03
Ash (%)	1.26	0.20
Fiber (%)	-	0.35
Energy (kcal/100 g)	275.73	271.11

Several studies have been conducted on the energy content of commercial jams, with an emphasis on those containing added sugar. These studies have revealed that commercial jams typically possess an energy content ranging from 271 to 280kcal/100g (Mohd Naeem et al., 2017; Negrea et al., 2025). The energy content of cocoa mucilage jam, which does not contain added sugar, was on average 275.73kcal/100g. This finding demonstrated that cocoa mucilage jam naturally provides energy when consumed due to its macronutrient content.

5.7.2 Economic analysis

To determine the minimum profit each smallholder receives from marketing the jam, the production unit "La Soledad" was selected. This unit is located in the "Buzal" neighborhood of the Otanche municipality. This unit was chosen due to its status as the production unit with the lowest percentage of CCN-51 and ICS-95 varieties.

The production costs for 0.25 kg of cocoa mucilage jam encompassed Direct Material costs (DM), which incorporated materials and equipment; Direct Labor costs (DL), encompassing workers' wages; and Manufacturing Overhead (MOH), which included indirect materials and indirect labor (see Table 10).

Table 10. Production costs for 0.25 kg of cocoa mucilage jam. Source: Own elaboration.

Direct Material Costs (USD)*	0.87
Materials and equipment	
Direct Labor Costs (USD)*	1.55
Wages (1 jornal= 8 hours worked daily)	
Manufacturing Overhead (USD)*	1.20
Indirect materials and indirect labor	
Total (USD)*	3.62

*Exchange rate COP/USD = 4,129

The potential annual income per hectare was calculated by considering the average price of unsweetened jams in 0.25 kg presentations in Colombia, which was USD$5.21, and the cocoa pod husk and mucilage generated of the selected production unit, "La Soledad," which was 2,636 kg/ha in 2024. This cocoa pod husk and mucilage generated was integrated by 791 kg (30%) of CCN-51, 1,212 kg (46%) of ICS-95, and 633 kg (24%) of other varieties (see Table 11).

Table 11. Potential annual income per hectare. Source: Own elaboration.

Sample	Clone variety	Cocoa pod husk and mucilage (kg)	Volume of extracted mucilage juice (l)	Cocoa mucilage jam (kg)	Sale price for 0.25 kg (USD)*	Income (USD)*
1	CCN-51	791	114.04	24.22	4.97	481
2	ICS-95	1,212	164.85	29.31	4.97	582

*Exchange rate COP/USD = 4,129

The cocoa pod husk and mucilage generated by "La Soledad" demonstrated that it is possible to extract 278.91 liters of mucilage juice per hectare to produce 53.54 kg of cocoa mucilage jam, with a sale price of USD$4.97 for 0.25 kg. This price was lower than the average price of similar products on the Colombian market, which was USD$5.21. A comparison of the production costs of USD$3.62 and the sale price of USD$4.97 indicated a profit margin of 27%. This is advantageous for cocoa smallholders because it enables them to enter the market at a competitive price without affecting profits. The annual income was determined to be USD$1,063.

The mean annual income from cocoa bean sales in "La Soledad", as indicated by the survey data, was USD$4,360. The potential annual income from jam sales was calculated to be USD$1,063, which is equivalent to 24% of the income from cocoa bean sales received. The findings indicated that the management of cocoa waste in production units yielded environmental, economic, and social benefits. It generated additional income, averted potential environmental concerns, and fostered a stronger sense of unity and collaboration among smallholders.

5.8 Participatory mapping

The roadmap of the participatory mapping was based on the nine variables obtained from the Principal Component Analysis (see Annex 4). The georeferencing and rasterization of each participant's map was conducted using ArcGIS software, enabling the precise determination of their geographical location and subsequent analysis in vector format. The mapping process was supported by a roadmap encompassing ten topics, involving both present and future scenarios.

Smallholders identified four potential agrotourism routes that integrated the three dimensions of sustainability (see Figure 26). In the environmental dimension, the focus was on water and forest resources; in the economic dimension, strategic marketing points were identified; and in the social dimension, associative work activities were proposed.

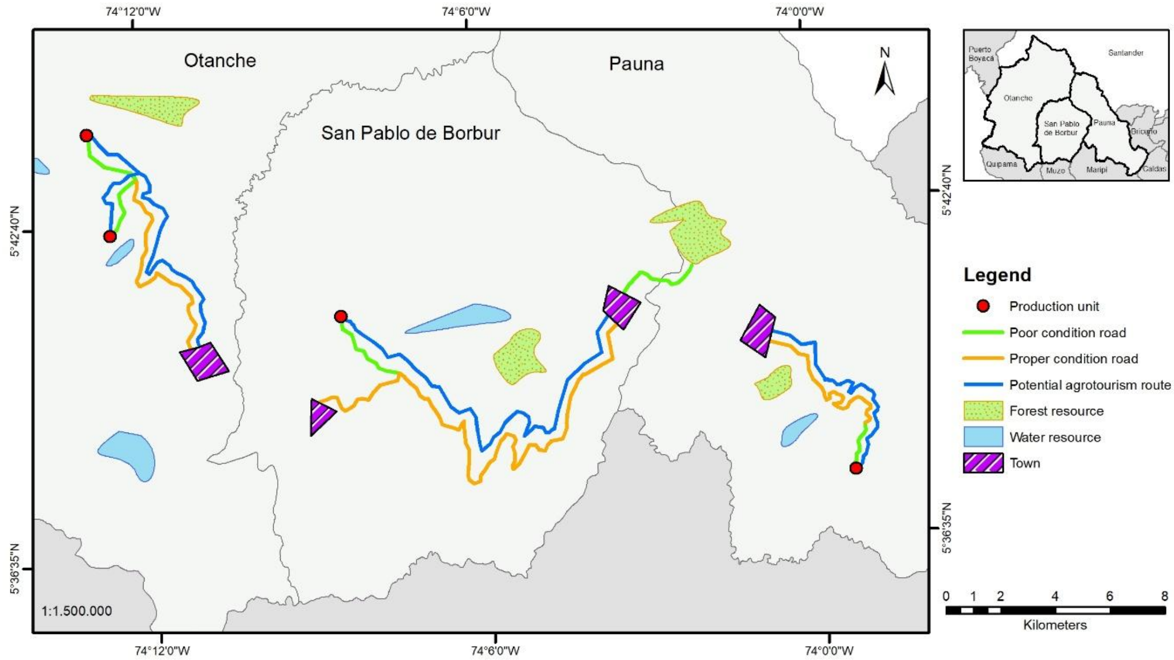

Figure 26. Map of potential agrotourism routes. Source: Own elaboration using ArcGIS software.

The present scenario was predicated on the marketing of the food by-product, namely, cocoa mucilage jam. The establishment of two working groups, operating within two of the three participating associations, was initiated to explore the potential of cocoa waste utilization for marketing purposes in local and regional markets. The future scenario was predicated on the implementation of a marketing strategy disseminated through four potential agrotourism routes. This strategy focused on raising consumer awareness concerning the production process of cocoa mucilage jam and its environmental, economic, and social impact on the cocoa value chain.

Smallholders selected the four production units of the Otanche-San Pablo de Borbur-Pauna corridor with the greatest potential for agrotourism. The municipalities of Pauna and San Pablo de Borbur each included one unit, while Otanche integrated two production units. The selection of these units was based on a comprehensive analysis of various factors, including geographical location, temporal accessibility, available transportation options, road conditions, and proximity to areas with water and forest resources that are conducive to tourism. While the secondary roads are in poor condition, the primary roads leading to the four units are in proper condition, and the time of connection to the town is less than 30 minutes.

6. DISCUSSION

In the department of Boyacá, the implementation of circular flows in agricultural activities has been demonstrated to result in a substantial reduction in waste and external inputs, as well as the emergence of new business opportunities. These findings complement research such as that carried out by Human et al. (2023), which yielded that the integration of continuous cycles in the cocoa value chain promoted the development of circular business models, which showed enhanced income levels and living conditions for cocoa farmers.

The quality of the food by-product developed in this research, as well as other products with potential development in this region, is contingent upon the implementation of Good Agricultural Practices (GAP) by smallholders in their production units. A notable aspect of this implementation is the shift towards the utilization of organic fertilizers. Studies have demonstrated that organic fertilization enhances both the quality and quantity of harvested products. A notable case study is that of Sinaga et al. (2023) in Indonesia, which demonstrated that the application of 10 tons of organic fertilizer per hectare led to a 296.10% increase in the number of cocoa pods compared to the control plants.

The implementation of initiatives for the generation of circular flows requires the involvement of smallholders, a commitment that must be endorsed by all actors within the cocoa value chain. The disintegration of the actors within the value chain has had deleterious effects on the weakest link, the smallholder. Due to their limited resources, smallholders are unable to confront challenges such as increasing production losses resulting from climate change and the prevalence of diseases and pests (Tham-Agyekum et al., 2024). Production losses are directly related to economic losses. According to estimates made by Jung et al. (2020) Peru and Colombia would incur the highest economic losses in 2050 due to the loss of more than 20% of cocoa bean weight caused by diseases and pests, equivalent to over USD$12 million and USD$6.5 million, respectively.

An alternative to face economic losses is the marketing of new by-products derived from cocoa organic matter. The present study explored the strategic initiatives employed by smallholders in the context of post-harvest processing. A notable action point that emerged from this research was the utilization of organic matter, which is readily available due to its generation during the post-harvest process within the production unit. Following Anoraga et al. (2024), the cocoa organic matter has a high potential to be transformed into new marketable products, thereby generating profitable outcomes.

In the Otanche-San Pablo de Borbur-Pauna corridor, the development of new products based on the use of organic matter has the potential to contribute to the green business sector of the department of Boyacá. Gobernación de Boyacá (2020a) in its green business map (see Figure 27), demonstrated that before 2020, there was no development of initiatives in the category of recovery and valorization of waste in this corridor.

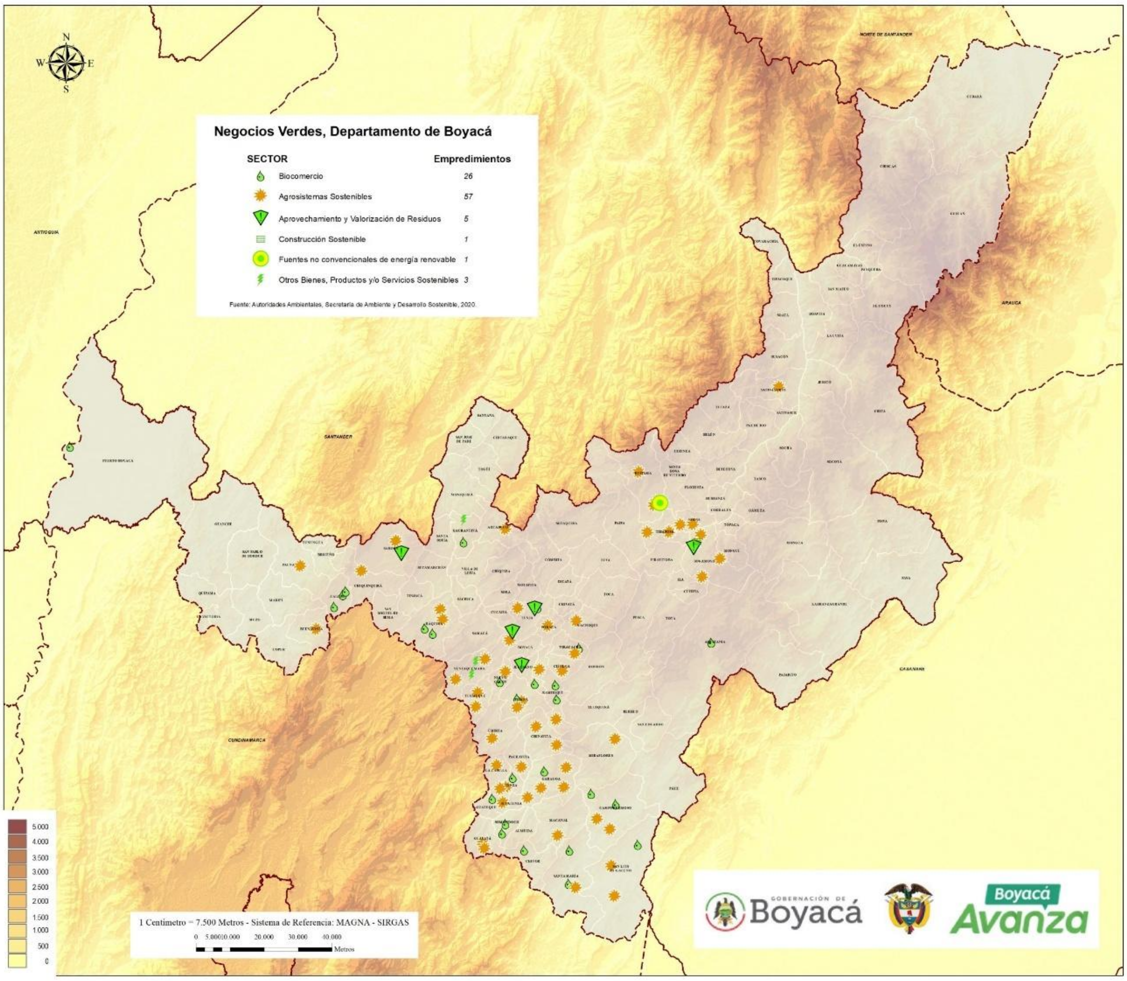

Figure 27. Green business map of the department of Boyacá. Source: Gobernación de Boyacá, 2020a.

The development of a cocoa food by-product involved a process and an outcome. The outcome was evident in the generation of income from the sale of the product, and the process was exemplified by the enhancement of associativity among smallholders, who exchanged experiences and disseminated knowledge through partner meetings. The significance of smallholders' associations within the cocoa value chain is twofold. Firstly, these associations facilitate access to timely information, which is crucial for smallholders to make informed decisions. Secondly, they promote collaborative problem-solving, which is essential for addressing challenges and enhancing resilience in the face of natural hazards (Tham-Agyekum et al., 2024).

The role of knowledge management in the functioning of value chains is a critical factor in achieving operational excellence. In the present research, knowledge management played a pivotal role in the transformation of cocoa waste. Through focus groups and participatory mapping, smallholders converged to exchange personal and collective experiences regarding the development of food by-products. This collaborative effort aimed to yield a high-quality product. This finding indicates that the exchange of knowledge among smallholders, whether directly or through associations, enhances both vertical and horizontal relationships within the cocoa value chain (Gutiérrez Garcia et al., 2025).

The development of RECOIN methodology was characterized by the notable involvement of women smallholders, who proactively established two working groups to address the utilization of cocoa waste. The integration of women into value chains has been demonstrated to catalyze the promotion of entrepreneurship and the generation of employment opportunities. Consequently, this integration has been shown to enhance the quality of life for both women and their families (Malapit et al., 2020; Maertens & Verhofstadt, 2013).

The support of government institutions is indispensable for the maintenance and development of Global Agricultural Value Chains. The economic and social upgrading of smallholders is enabled by factors such as regulatory frameworks, institutional support, infrastructural development, and partnerships (Kissi & Herzig, 2024). Nonetheless, the presence of government institutions in the cocoa value chain in Colombia is not a salient feature. This assertion is supported by the finding that 71% of the smallholders who participated in this research acknowledged that the government's contribution is minimal, with the predominant source of support stemming from associations of smallholders.

Product diversification in the cocoa value chain serves as an economic leverage tool for smallholders, as exclusive dependence on seed sales can increase their vulnerability to commodity price volatility. Research conducted by Tröster et al. (2019) in Côte d'Ivoire and Ghana demonstrated that domestic price stabilization mechanisms are ineffective in protecting producers from inter-seasonal price variations, thereby placing the greatest burden of variability on producers.

Sustainability within the cocoa value chain has emerged as a pivotal concern, particularly in the context of the increasing focus by major cocoa-producing nations. This issue is compounded by the externalities faced by smallholders daily, including the challenges posed by pests, diseases, low productivity, an excess of marketing intermediaries, and limited support from government institutions (Leksono et al., 2021; Sa’adah et al., 2024). In the Otanche-San Pablo de Borbur-Pauna corridor, smallholders have been observed to cope with these externalities by implementing agroforestry and organic cultivation. However, constant advice from research institutions promoting the improvement of these measures is required.

The cocoa value chain in the department of Boyacá is confronted with the challenge of integrating new technologies. The implementation of new technologies has the potential to transform the material and process flows of agricultural activities. This transformation has been demonstrated to exert a favorable influence on the socio-economic well-being of cocoa smallholders (Souza, 2024). The technological gap requires the collaborative engagement of public and private institutions. This collaborative effort is essential for smallholders to develop new skills and generate knowledge surrounding technological appropriation in their daily cultivation routines.

7. CONCLUSIONS AND RECOMMENDATIONS

The analysis of the impact of the selected circular agriculture practice, reduction of waste generated, and the utilization of organic matter as a specific action point, on the sustainability of the cocoa value chain in the Otanche-San Pablo de Borbur-Pauna corridor revealed a favorable impact on the environmental, economic, and social dimensions, thereby supporting the hypothesis proposed.

In the 24 production units selected for the study, the implementation of circular agriculture practices resulted in the development of a potentially marketable food by-product, namely, cocoa mucilage jam. The production of this jam required 278.91 liters of mucilage juice per hectare, which used to be classified as waste. This initiative led to a reduction in the negative environmental impact caused by cocoa pod husks stacked in production units without proper treatment.

Cocoa mucilage jam has been shown to have a high nutritional content, specifically of proteins and fats, when compared to commercial jams. The energy content of cocoa mucilage jam, which does not contain added sugar, was on average 275.73kcal/100g. This value was found to be comparable to that of commercial jams, which contain added sugar, and their energy content ranged from 271 to 280kcal/100g.

The developed food by-product was a cost-effective alternative for smallholders, as it generated a profit margin of 27% and an income equivalent to 24% of the cocoa bean sales received. This alternative promoted the inclusion of women smallholders in the economic dynamics of cocoa mucilage jam production and marketing.

The development of the RECOIN methodology demonstrated that knowledge management among smallholders was predicated on associativity. To identify the most effective strategy for implementing circular flows within the agricultural activities of the cocoa value chain, smallholder associations from each municipality of the Otanche-San Pablo de Borbur-Pauna corridor collaborated to exchange knowledge and experiences.

Through agrotourism routes, smallholders proposed to disseminate knowledge about the production process of cocoa mucilage jam beyond the sale of this food by-product. The proposal entailed the establishment of four agrotourism routes, designed to facilitate interaction between smallholders and consumers, thereby enhancing awareness of the environmental, economic, and social implications of cocoa waste processing.

The implementation of the proposed agrotourism routes is contingent upon the involvement of government institutions responsible for the maintenance and repair of roads, given the poor conditions of the roads connecting production units with primary transportation routes. The logistical challenges associated with the transportation of raw materials and products from production units to primary transportation routes have limited the emergence of commercial initiatives due to the high costs generated by this process.

The establishment of two working groups about the use of organic matter demonstrated a strong connection between smallholders and circular agriculture practices, as well as an escalating inclination to explore new markets. Smallholders shifted their exclusive focus to the extraction and marketing of cocoa seeds. The incorporation of new products into their portfolio has enabled diversification, thereby prolonging the materials' presence in the productive cycle and reducing waste generation.

The relationship between smallholders and public and private institutions in the department of Boyacá has been facilitated by the implementation of programs developed at the national level as part of cooperative strategies, such as "Cacao para la paz" and "Familias Guardabosques". However, the actors of the cocoa value chain who were included in this study stated a persistent tendency among institutions to engage in projects that are focused on making value chain diagnoses. This has resulted in the production of numerous diagnoses of a similar nature that lack actionable strategies.

This research has proposed the RECOIN methodology for the development of circular economy alternatives in agricultural value chains. An implementation of this methodology in other agricultural value chains with a larger sample size is recommended. Such a size would allow for an in-depth analysis of the environmental, economic, and social characteristics of a region. It would also increase the precision of results and reduce the margin of error.

This research identified variables in each of the dimensions of sustainability that link circular agricultural practices in the cocoa value chain. It is recommended that these findings be considered in future studies involving actions on the environmental, economic, and social sustainability of the agricultural activities in the cocoa value chain at both global and national levels.

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9. ANNEXES

9.1 Annex 1. Survey for cocoa smallholders

Name	
Age	
Gender	Female________ Male__________
Neighborhood	
How long have you lived there?	
What level of education do you have?	Elementary school incomplete Elementary school complete High school incomplete High school complete Technician Professional Other:
Do you have access to public utilities for water, electricity, gas, waste collection, Internet?	Yes______ No______
Do you belong to a producer association?	Yes______ No______ Which?
What is the area planted in hectares? On average, how many cocoa trees?	
The farm where you live is:	Own________ Leased________ Other:
How many people are in your family? Who are they?	
How many people work in your Production Unit (farm)?	
How many days a week?	
How much is the daily wage per person?	
Do you plant in agroforestry system?	Yes______ No______ Why?
Do you plant cocoa in association with another crop?	Yes______ No______ Which?
What variety of cocoa do you plant?	
How many harvests do you have per year? In what months?	
What is the yield of your crop (Ton/ha) or (Kg/ha)?	
How much annual production (Ton) or (kg) of cocoa do you have?	
Where do you get the water for your crop?	
What irrigation system do you use?	None

	Rain Drip Sprinkling Automated Other:
Do you reuse the water you use during the processes of planting, harvesting, fermentation and drying?	Yes______ No______
If you answered Yes to previous question In what process and how?	
If you answered No to previous question What is the destination of the water used?	
Do you use pesticides in your crops?	Yes______ No______ What amount per year?
Have you performed or do you perform biological pest control?	Yes______ No______ With which organisms?
Do you use chemical fertilizers on your crops?	Yes______ No______ What amount per year?
How much money do you invest in the purchase of chemical fertilizers?	Monthly______________ Annual______________
Do you use organic fertilizer?	Yes______ No______ What amount per year? Do you buy it or produce it?
Do you think that soil productivity can be maintained by using only organic fertilizers?	
Do you raise animals?	Yes______ No______ How many and which ones?
What do you do with the manure generated by the animals?	
What type of drying is performed in the beneficiation process?	Natural______ Artificial______ Why?
How much is the annual generation (Ton) or (Kg) of pod and mucilage?	
What material are the dry grain packaging bags made of and what is their capacity?	
How much is your income from cocoa bean sales?	
On average, how much do your monthly expenses amount to?	$600.000 - $800.000 COP $800.000 - $1.000.000 COP Más de $1.000.000 COP Other:
Have you received or are you receiving training on cocoa pod and mucilage utilization?	Yes______ No______
Which institution has provided the training?	

Do you have any transformation or reuse process for cocoa pod and mucilage?	Yes______ No______ Which?
If you answered Yes to the previous question. How much does it cost to carry out this process?	
If you answered Yes to the previous question. How much is your income from sales of transformed or reused product?	
If you answered No to the previous question. Do you think that new products could be generated from cocoa pods and mucilage?	Yes______ No______ What type of products?
Do you have any process of transformation or reuse of branches, leaves, pruning remains?	Yes______ No______ Which?
How do you consider the participation of government institutions in the cocoa production chain in the municipality?	Good Fair Poor Why?
What do you think is your level of access to technologies that allow you to improve the cocoa production process?	Good Fair Poor Why?
Do you have any government support for access to technologies to improve the cocoa production process?	Yes______ No______ Which?
Are your products or processes certified?	Yes______ No______ Which?
Do you export your products?	Yes______ No______
Who do you sell your production to?	
What percentage of production is lost in each harvest?	
What are the main causes of production loss?	
What do you do with the cocoa that is lost in each harvest?	
How much do you estimate the economic losses due to crop loss?	
Do you have a loss minimization plan?	Yes______ No______ What does it involve?
Do you think it is a good practice to reuse natural resources?	Yes______ No______ Why?
Do you believe that your Production Unit (farm) has the conditions to implement any natural resource reuse practices?	Yes______ No______ Which?
Were you or are you part of any crop substitution program?	Yes______ No______ Which?
What are the benefits of this program?	

9.2 Annex 2. Focus group for cocoa smallholders

Dimension	Variable	Question	Details
Environmental	Annual_production	What is your position on the use of fertilizers and pesticides in cocoa cultivation?	• Type of fertilizer • Type of pesticides • Knowledge about final destination • Preferences
	Organic_fertilizer		
	Production_losses		
Economic	Cocoa_sales	Which circular agriculture practices develop, or would you implement in your cocoa crops with a positive impact on the environment, the economy and society?	• Type of practice • Frequency • Results • Individual or collective practice
	Economic_losses		
	Cocoa_trade		
	Cocoawaste_reuse		
Social	Association_Membership	How do you disseminate your knowledge to other smallholders?	• Type of knowledge • Associativity • Knowledge management • Organization • Use of technologies
	Hectare_PU		

9.3 Annex 3. Semi-structured interview for technicians and managers of the cocoa value chain

Dimension	Variable	Question	Details
Environmental	Annual_production Organic_fertilizer Production_losses	What is your position on the use of fertilizers and pesticides in cocoa cultivation?	• Type of fertilizer • Type of pesticides • Knowledge about final destination • Preferences
Economic	Cocoa_sales Economic_losses Cocoa_trade Cocoawaste_reuse	Which circular agriculture practices are being developed or could be implemented in cocoa cultivation with a positive impact on the environment, the economy, and society?	• Type of practice • Frequency • Results • Individual or collective practice
Social	Association_Membership Hectare_PU	How is knowledge managed among the various actors involved in the cocoa value chain?	• Type of knowledge • Associativity • Knowledge management • Organization • Use of technologies

9.4 Annex 4. Participatory mapping for cocoa smallholders

<table>
<tr><th>Variable</th><th>Present</th><th>Future</th></tr>
<tr><td rowspan="2">Cocoa_Trade</td><td colspan="2">Identify the process of transport of products from the production unit to the marketing area.</td></tr>
<tr><td>• Place of residence
• Production Unit
• Routes and times
• Road conditions
• Means of transport</td><td>• Place of residence
• Production Unit
• Routes and times
• Road conditions
• Means of transport</td></tr>
<tr><td rowspan="2">Organic_fertilizer</td><td colspan="2">Identify water use, importance to smallholders, and knowledge of places that ensure the availability of water in the region.</td></tr>
<tr><td>• Use of water
• Areas with water availability</td><td>• Use of water
• Areas with water availability to preserve and/or recover</td></tr>
<tr><td rowspan="2">Organic_fertilizer
Production_losses</td><td colspan="2">Identify how smallholders relate the use of chemical pesticides and fertilizers to their impact on the environment in the region they inhabit.</td></tr>
<tr><td>• Areas affected using pesticides and chemical fertilizers</td><td>• Areas where pesticide and chemical fertilizer use should be reduced</td></tr>
<tr><td rowspan="2">Association_Membership</td><td colspan="2">Identify how actions taken by government institutions in the region have impacted cocoa crop development.</td></tr>
<tr><td>• Government decisions affecting production units</td><td>• Actions that decision makers should consider</td></tr>
<tr><td rowspan="2">Economic_losses
Cocoa_sales</td><td colspan="2">Identify how the income and economic losses received in each harvest relate to the geographical location of each production unit.</td></tr>
<tr><td>• Production route
• Marketing route
• Road conditions
• Means of transport</td><td>• Production route
• Marketing route
• Road conditions
• Means of transport</td></tr>
<tr><td rowspan="2">Association_Membership</td><td colspan="2">Identify the focal points where associative activities are developed that generate community organization around cocoa cultivation.</td></tr>
<tr><td>• Specific activities or meetings</td><td>• Specific activities or meetings</td></tr>
</table>

Hectare_PU	Identify places where smallholders acquire technical knowledge and access to technologies that improve their day-to-day activities.	
	• Training places • Routes and times • Road conditions • Means of transport	• Training places • Routes and times • Road conditions • Means of transport
Hectare_PU Annual_production	Identify land use in the Production Units and possible future changes.	
	• Land use in the production unit	• Land use in the production unit
Cocoawaste_reuse	Identify the marketing route of smallholders who sell products made of organic matter.	
	• Marketing points • Routes and times • Road conditions • Means of transport	• Marketing points • Routes and times • Road conditions • Means of transport
Cocoawaste_reuse	Identify transport, storage and processing requirements for cocoa waste.	
	• Waste management places • Routes and times • Road conditions • Means of transport	• Waste management places • Routes and times • Road conditions • Means of transport