

Chapter

Past, Present, and Future of Coffee Crop Sustainability in Colombia: Lessons Learned from Scientific Research and Rural Extension

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Abstract

Colombia has long been recognized for its high-quality Arabica coffee production, supported by a robust research and extension system led by the National Federation of Coffee Growers of Colombia, along with its institutions, Cenicafé and the Extension Service (ES). Over the past decades, Cenicafé has played a central role in advancing the sustainability of coffee cultivation through scientific research, technological innovation, and rural extension. This chapter explores the historical evolution, current strategies, and future outlook of sustainable coffee production in Colombia. It highlights key milestones, such as the development of leaf coffee rust-resistant varieties such as Castillo, the implementation of integrated pest and disease management practices, and the promotion of agroecological approaches to reduce environmental impacts. The ES has been instrumental in translating research findings into practical solutions adopted by thousands of smallholder farmers. As climate change and environmental challenges threaten the resilience of the coffee sector, future sustainability efforts will require an even stronger alignment between science, policy, and community-based innovation. The Colombian model offers valuable lessons for other coffee-producing countries aiming to balance productivity, environmental stewardship, and rural livelihoods.

Keywords: coffee, sustainability, production systems, regenerative crop management, technological innovation

1. Introduction

Coffee cultivation in Colombia constitutes a strategic pillar of the national economy, not only due to its significant contribution to the agricultural gross domestic product but also because of the country's international recognition as a leader in the production of high-quality mild-washed Arabica coffees. Currently, coffee-farming in Colombia represents the main economic activity for more than 557,000 families who cultivate the crop on an area of approximately 835,000

hectares. This highlights a productive structure based on smallholder farming systems, with average farm sizes of less than 1.5 hectares per producer.

For nearly a century, the Colombian coffee sector has been an international benchmark for collective organization, represented by the Colombian Coffee Growers Federation (FNC). Founded in 1927 by a group of visionary coffee growers with the initial purpose of expanding the commercialization of Colombian coffee in international markets, the FNC has consolidated itself as a democratic and representative organization that, from its inception, established institutional financing mechanisms aimed at promoting research and rural extension as keystones of the modernization and sustainability of coffee production systems.

The Sustainable Coffee Management (SCM) approach in Colombia seeks to achieve a comprehensive balance among economic viability, social well-being, and environmental stewardship throughout all stages of the production process. SCM is oriented toward the adoption of practices and technologies supported by scientific research generated by the National Coffee Research Center (Cenicafé) and efficiently transferred to coffee growers through the FNC's Extension Service (ES).

Economic sustainability of coffee production systems is based on profitability as an essential condition to ensure that producers remain engaged in the activity, focusing on their ability to generate sufficient income from their respective roles in coffee production to enable them to live a dignified life [1]. Since 2016, the FNC has been implementing at the national level the strategy “More Agronomy, More Productivity, More Quality,” whose main objective is to promote the widespread adoption by coffee growers of eight key agronomical practices to reach high yields and seven post-harvest practices that ensure the production of high-quality coffee [2]. Social sustainability, in turn, considers the impacts of coffee-farming on people, including decent working conditions, the eradication of child labor and land grabbing, as well as proactive steps to improve the food security of coffee-growing families [1]. Environmental sustainability of Colombian coffee-growing is grounded in ensuring the continuous availability of resilient ecosystem services and the preservation of conserved nature [1]. This dimension encompasses all actions aimed at conserving, restoring, and enhancing healthy ecosystems, biodiversity, water and soil quality; promoting ecosystem services; carbon sequestration; transitioning toward clean energy and bio-inputs; ensuring the sustainable use of waste; and safeguarding the environment throughout the coffee production process [3].

This chapter provides a historical overview of the evolution of coffee sustainability in Colombia, highlighting how research and rural extension have driven the adoption of sustainable management practices among producers. These efforts have helped shape a production model that fosters economic development, reinforces social well-being, and safeguards the ecosystems that support the cultivation of one of the world's smoothest coffees.

2. Typification of Colombian coffee-growing

Colombian coffee is cultivated across a wide range of eco-regions with diverse topographic, soil, and climatic characteristics. Geographically, the Colombian coffee zone is located in the Andean region between 1° and 12° north latitude and at altitudes ranging from 800 to 2,200 meters above sea level [4]. A large portion of the country's coffee farms are characterized by young soils (in a permanent state of

formation) belonging to the orders Inceptisols (60.7%), Andisols (17.6%), Entisols (10.5%), Mollisols (8.02%), and other orders (3.18%) [5]. The climate of the Colombian coffee region is strongly influenced by the Intertropical Convergence Zone and the mountainous relief of the three cordilleras, conditions that favor high cloudiness and intense rainfall, the dynamics of which are affected both by latitude and by El Niño and La Niña events [4]. Other climatic variables that favor coffee production include an annual mean temperature ranging between 19°C and 22°C and an average solar brightness of 1,500–1,800 hours per year [6].

The Colombian coffee zone covers a geographical area of more than 3.5 million hectares (*sensu lato*), hosting numerous ecosystems composed of tropical forests, watersheds, biological corridors, and natural reserve areas with a wide variety of species representative of the country's flora and fauna. According to the specific soil and climate conditions of the different coffee regions, Colombia's coffee production systems are classified into two types: (i) full-sun exposure systems and (ii) agroforestry systems (AFS) [6]. Full-sun exposure systems occupy 66% of the cultivated area, while AFS represent only 34% of the total area and are mainly located in low-altitude regions, where limited rainfall, high temperatures, and intense solar radiation create water-deficit conditions, further accentuated by soil properties that limit moisture retention during dry months [7].

Based on rainfall distribution regimes and harvest dynamics, Colombia is divided into three producing zones: (i) The southern zone, located between 1° and 3° north latitude, has a climatic regime characterized by higher rainfall between October and May, while June to September is drier, favoring the flowering that leads to harvests during the first half of the year; (ii) the central zone, located between 3° and 6° north latitude, presents a bimodal rainfall regime with two rainy periods per year (March to June and September to December), while January to February and July to August correspond to drier months. This condition results in a harvest distribution that fluctuates between 20% and 30% in the first semester and 70% and 80% in the second semester; (iii) the northern zone, located between 7° and 12° north latitude, shows a well-defined alternation of rainfall with higher precipitation between May and November and lower precipitation from December to April, favoring a harvest mainly concentrated in the second semester of the year [8]. This national dynamic of continuous harvest distribution allows exporters to consistently supply international markets with fresh coffee beans, a determining factor in preserving the sensory quality of Colombian coffee.

3. Sustainability challenges in coffee production

Colombian coffee-growing faces multiple challenges that affect the economic, social, and environmental dimensions of sustainability throughout the production chain. In the economic sphere, the profitability of coffee-farming is mainly undermined by reductions in productivity exacerbated by climatic events such as La Niña, as well as by fluctuations in international coffee prices resulting from changes in global supply and demand. On the social side, the main constraints include labor shortages, the aging of the coffee-farming population, youth migration from rural to urban areas, the declining vocation for agricultural work, precarious labor conditions, and the displacement of families due to armed conflict. In the environmental dimension, the negative impacts of coffee-farming on ecosystems

include biodiversity loss, deforestation, soil and water pollution, greenhouse gas emissions, and soil erosion.

Global markets are increasingly prioritizing agri-products sourced from sustainable production systems. A clear example is the new regulatory frameworks introduced under the European Green Deal and the European Union Deforestation Regulation, which directly affect Colombian coffee exports to Europe, accounting for approximately 33% of national production [3]. These emerging sustainability challenges have prompted the FNC to intensify institutional efforts aimed at fostering the transition from conventional production models toward more sustainable systems. This transition relies on the adoption of sustainable crop management practices by coffee producers, designed to generate positive outcomes for profitability, social well-being, and the integrity of the natural environment.

4. Scientific research and knowledge transfer model

Following the creation of the National Coffee Fund in 1940, a levy mechanism known as the coffee contribution was established, which currently amounts to USD 0.06 per pound of green coffee exported. These resources, historically managed by the FNC, are invested in four public goods aimed at strengthening Colombian coffee-growing: (i) scientific and technological research, (ii) rural extension, (iii) purchase guarantee, and (iv) international promotion of Colombian coffee [9]. This type of public investment, directed at strengthening the coffee value chain, has shaped a unique and highly successful model responsible for historic advances in productivity and quality, driven by the adoption of practices and technologies backed by the scientific research of Cenicafé and effectively transferred to producers through the FNC's ES.

4.1 Cenicafé

Founded in 1938, the National Coffee Research Center (Cenicafé) is a non-profit institution that serves as the scientific arm of the FNC. Its mission is to conduct scientific and technological research across 12 disciplines related to coffee: agroclimatology, biometrics, quality, economics, entomology, experimentation, physiology, plant pathology, crop science, plant breeding, post-harvest, and soils. Its main headquarters, the “Pedro Uribe Mejía” research station, encompasses approximately 100 hectares, of which 20 hectares are dedicated to facilities (laboratories, buildings, and processing facilities), while 80 hectares belong to the Planalto Forest Reserve, located in the rural area of Manizales, Caldas, Colombia. In addition, Cenicafé operates nine experimental stations distributed across the country, where field research is carried out.

Key assets of Cenicafé include the following: (i) The Coffee Climate Network, with more than 290 climatological stations distributed nationwide that record climate variables in coffee-growing regions and serve as essential inputs for farm-level decision-making, such as the monthly Coffee Agrometeorological Bulletin; (ii) The Colombian Coffee Collection, which includes 1,028 *Coffea* accessions obtained through explorations in the species' centers of origin and contributions from other international coffee research centers; this collection underpins research and the development of new varieties for Colombia; (iii) The Marcial Benavides

Gómez Entomological Museum, with 38,500 insect specimens collected since 1935, representing the biological diversity of Colombia's coffee regions; and (iv) The Alberto Machado Sierra Documentation Center, with more than 100,000 physical and digital documents on agricultural topics. The Cenicafé portal (www.cenicafe.org) provides open access to technical publications and resources designed to strengthen capacities for sustainable coffee production in Colombia, such as Technical Advances, the Cenicafé Journal, Coffee Agrometeorological Bulletins, Phytosanitary Bulletins, the Annual Cenicafé Report, and specialized technical books [10].

4.2 FNC ES

Since 1959, the FNC ES has provided continuous support to Colombian coffee growers through technology transfer and training in the sustainable management of coffee production systems. More than 1,000 extension agents play a central role in transferring the production and processing technologies generated by Cenicafé, employing a strategic combination of individual, group, and mass methods tailored to the needs of growers, the nature of the message, and the desired outreach [11].

Individual extension methods, such as farm visits, are particularly effective in establishing trust-based relationships with coffee growers, fostering personalized communication, and enabling a detailed analysis of each farm's specific context and challenges – an approach that increases the adoption rate of recommended management practices. During farm visits, extension agents directly observe farmers' realities, current practices, production conditions, limitations, and productivity potential, allowing them to formulate relevant and adapted solutions that respond not only to farmers' perspectives but also to the socioeconomic and environmental realities of each farm.

Group extension methods are essential for working with rural communities, as they allow extension agents to engage larger audiences, facilitating communication exchanges and strengthening interaction among participants. These settings enable the simultaneous training of significant numbers of people without losing a personalized approach, thereby enhancing efficiency in knowledge transfer. Among the main tools used in group activities are demonstrations of methods, meetings, field tours, field days, short courses, contests, and forums – all designed to promote collective learning and the adoption of sustainable agricultural practices. These methods are specifically structured to provide technical, economic, administrative, and financial training, enabling coffee growers to improve farm planning, crop management, and make better-informed decisions.

Mass extension methods represent an effective strategy for reaching many coffee growers, particularly those who cannot be reached through individual or group methods. Although these methods do not provide direct interaction between extension agents and communities, their main advantage lies in their low cost and rapid dissemination of messages. Through channels such as seminars, exhibitions, bulletins, brochures, articles in specialized publications, radio programs, posters, and banners, it is possible to disseminate technical information, practical recommendations, and institutional messages in a timely and accessible manner. Proper use of these methods helps strengthen institutional presence in the field and ensures broader coverage of training and support processes, thereby fostering the sustainable and integral development of the coffee sector [11].

5. Evolution of SCM in Colombia

Coffee cultivation management encompasses a suite of agronomic practices designed to optimize the biological performance and productivity of coffee plantations. This involves the regulation of intra and interspecific competition, mitigation of losses due to biotic and abiotic stressors, and the implementation of strategic decisions regarding cultivar selection, renovation cycles, planting dates, and sowing densities [9]. Additionally, it includes the design of spatial arrangements, soil fertility and nutrient management, phytosanitary interventions, and the optimization of harvest and post-harvest processes.

The evolution of traditional coffee production dynamics in Colombia has been driven not only by the imperative to enhance productivity and reduce impacts on the ecosystems where the crop is cultivated but also by phytosanitary challenges, including the coffee leaf rust outbreak in the early 1980s and the arrival of the coffee berry borer in the 1990s. These limitations have been further compounded by climate change and the increasing sustainability demands of global coffee markets.

Colombian coffee cultivation began in the eighteenth century with the introduction of the first *Coffea Arabica* seeds of the Typica and Bourbon varieties. These tall varieties (reaching plant heights of 2.5 to 4.5 meters) with superior cup quality were widely cultivated until the 1960s, when the Caturra variety emerged. Caturra, a highly productive dwarf cultivar, is regarded as the first coffee variety associated with the Green Revolution in Colombia, as its compact architecture enabled higher planting densities and facilitated more intensive fertilizer use, thereby unlocking greater yield potential compared to traditional cultivars such as Typica and Bourbon [12]. Between 1960 and 1983, Caturra became the most widely planted variety, until the appearance of coffee leaf rust (*Hemileia vastatrix* Berk. & Br.) in the country. This disease causes severe defoliation in coffee plants, leading to cumulative production losses of 23–50% and negatively impacting bean physical quality. To address this threat, Cenicafé had already developed, by 1975, the Colombia[®] variety derived from a cross between Caturra and the Timor Hybrid, becoming the first rust-resistant variety, which was massively adopted by coffee growers as the main genetic management strategy against the disease [13].

The Colombia[®] variety was widely cultivated in the country between 1983 and 2000. Subsequently, Cenicafé has released many varieties, such as Tabi[®] (2002), Castillo General[®] and Castillo Regionales[®] (2006), Cenicafé 1[®] (2016), Castillo Zonales[®] – North, Center, and South (2017), and Castillo 2.0[®] (2024) [13]. All these multi-line varieties (composed of multiple progenies) exhibit high resistance to coffee leaf rust and to coffee berry disease caused by the fungus *Colletotrichum kahawae*, a devastating disease in Africa that has not yet been reported in Colombia [14]. Moreover, they present wide environmental adaptability, high productive potential, and excellent cup quality, making them the first recommendation for sustainable management among Colombian coffee growers.

In 1988, the coffee berry borer (*Hypothenemus hampei* Ferrari) was detected for the first time in Colombia. This pest expanded rapidly, and by 1997, it was estimated to be present in approximately 703,000 hectares [15]. One of the greatest challenges in controlling this insect relates to its biology and behavior, as adults shelter inside coffee cherries and have a high reproductive capacity favored by high temperatures – conditions that complicate its management. The pest's rapid spread initially led to the indiscriminate use of highly toxic insecticides, negatively

affecting beneficial fauna and compromising coffee safety. In response to this problem, Cenicafé established an Integrated Pest Management program encompassing cultural practices such as timely harvesting, multiple pickings, collection of fallen fruits, and sanitary harvesting, alongside biological control using the entomopathogenic fungus *Beauveria bassiana* [16]. In addition, action thresholds were established for chemical control (based on field monitoring and flowering records), recommending treatment when the infestation rate per tree exceeded 2% and when more than 50% of the insects were penetrating the fruit (positions A and B). Moreover, biological control through the release of parasitoid wasps (*Cephalonomia stephanoderis*, *Prorops nasuta*, and *Phymastichus coffea*) constitutes a promising strategy validated and recommended by Cenicafé for the sustainable management of this pest [17].

Once integrated management strategies for coffee leaf rust and the coffee berry borer had been defined, research efforts focused on identifying the agronomic management factors that most influenced the economic sustainability of Colombian coffee production systems. Using Cobb–Douglas production functions, Cenicafé determined that planting density (number of plants per hectare) and plantation age were the most influential factors on farm productivity [18]. Based on these findings, extensionists recommend increasing planting densities of dwarf-intermediate varieties (e.g., Castillo[®], Cenicafé 1[®]) to densities of 6,000–8,000 plants/ha, while tall varieties (e.g., Tabi[®]) are limited to 5,000 plants/ha. Additionally, by analyzing coffee production elasticity curves across different regions, Cenicafé identified the optimal ages for plantation renewal, providing technical guidance for replanting or stumping interventions to maintain long-term productivity stability [18].

Another fundamental pillar of sustainable coffee cultivation management in Colombia relates to sustainable soil management, which integrates conservation practices to reduce erosion, manage soil acidity, and optimize crop nutrition. Soil conservation practices include contour planting, cover crops, selective weeding, living barriers, trenches, and drainage systems [19]. Soil acidity management involves the application of amendments with oxides, hydroxides, and carbonates of calcium and magnesium, which neutralize acidity when soil pH is below 5, increasing nutrient availability and enabling normal root development of coffee plants [20]. Adequate crop nutrition is determined by soil analyses and the specific nutritional requirements of the coffee plants at each physiological stage. These parameters define the selection of fertilizer sources, as well as the timing, dosage, and method of application required to maximize nutrient use efficiency. Recent research at Cenicafé has focused on organo-mineral fertilization strategies, in which chemical fertilizers are combined with organic sources such as coffee pulp. This integrated approach enhances nutrient cycling, reduces dependency on chemical fertilizers, and provides both economic and environmental benefits for coffee production systems [21] (**Figure 1**).

To reduce the risks associated with monoculture, Cenicafé promotes the implementation of diversified systems that integrate shade trees and food crops (e.g., maize, beans, and bananas) intercropped with coffee. This sustainable practice helps regulate the microclimate, mitigating the negative effects of water deficits, high temperatures, and excessive solar radiation. Additionally, the establishment of AFS with tree species such as *Albizia carbonaria*, *Inga spp.*, *Cordia alliodora*, and *Erythrina fusca* provides ecosystem services, including nutrient cycling, soil fertility improvement, erosion control, water retention, carbon sequestration, biodiversity



Figure 1. Key management factors for achieving high productivity in coffee production systems in Colombia.

conservation, and climate regulation [22]. Furthermore, to enhance climate resilience, decision-making on SCM is based on the analysis of agroclimatic variables recorded in different coffee-growing regions of the country. This information, generated by the Coffee Agroclimatic Network and available through Cenicafé’s Agroclima portal [7], allows producers to understand climatic patterns as well as the incidence of large-scale climate events such as El Niño and La Niña, which have a direct effect on crop productivity.

One of the main sources of soil and water contamination in coffee production is the inadequate management of wastewater generated during wet processing. To address this challenge, Cenicafé has developed a set of innovative technologies now accessible to coffee growers. The BECOLSUB[®] system allows depulping without the use of water and ensures controlled mixing of pulp and mucilage, resulting in 77.5–83.8% reductions in chemical oxygen demand and a substantial decrease in the volume of polluting effluents. The Ecomill[®] technology further increases processing efficiency by reducing water consumption during washing to 0.35–0.6 liters per kilogram of dry parchment coffee (DPC), while eliminating wastewater discharges [23]. In situations where effluents are generated, Cenicafé developed the Modular Anaerobic Treatment System, a scalable bioreactor consisting of modular tanks designed to remove organic pollutant loads with treatment efficiencies above 80%. More recently, the Green Filter[®] technology has emerged as an advanced solution capable of eliminating 100% of wastewater contamination from wet processing by leveraging the combined purifying capacity of soils and vegetation through total evapotranspiration, thus achieving zero liquid discharge [24]. Taken together, these technologies enhance the sustainability of coffee processing by drastically reducing water demand, significantly lowering pollutant emissions, and protecting both soils and aquatic ecosystems.

Currently, new trends in SCM emphasize the adoption of regenerative agriculture principles and practices – a holistic approach that transcends the traditional concept of sustainability by aiming not only to mitigate environmental impacts but also to actively restore and enhance the functioning of coffee agroecosystems. At Cenicafé, regenerative coffee management is framed around five core principles: (i) soil health, (ii) water quality, (iii) biodiversity, (iv) climate action, and (v) rural livelihoods (**Figure 2**). The overarching goal is to develop resilient and competitive production systems capable of meeting the growing demand for sustainably produced coffee in international markets [25].

Within this regenerative framework, the circular economy has emerged as a strategic axis to valorize coffee by-products such as pulp, mucilage, and wastewater through their transformation into biogas, compost, biochar, and bio-inputs. These products have the potential to partially substitute synthetic inputs, thereby reducing reliance on external resources, lowering environmental pollution, and complementing nutrient plans at the farm level. This approach not only mitigates the environmental risks inherent to coffee production but also generates new economic opportunities for farmers by converting materials traditionally regarded as waste into value-added resources.

In summary, the convergence of regenerative agriculture, circular bioeconomy, and bio-input innovations provides a pathway toward a coffee production model

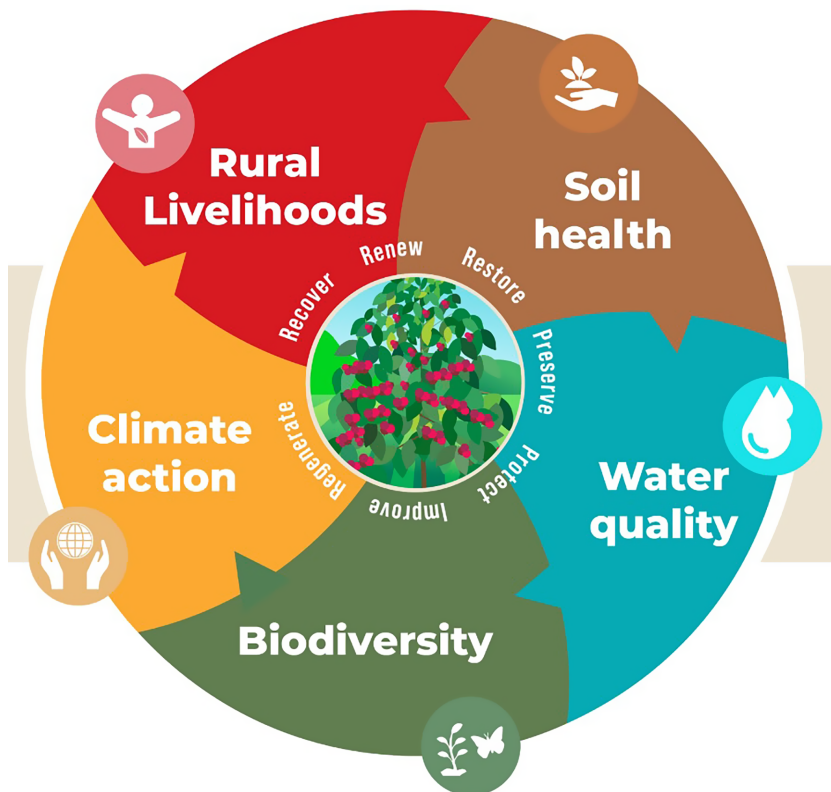


Figure 2.
Five core principles of regenerative coffee management.

that ensures long-term sustainability while simultaneously regenerating ecosystems, diversifying rural incomes, and strengthening the resilience and equity of coffee-based livelihoods.

6. Conclusion

The research outcomes generated by Cenicafé and effectively disseminated through the coffee growers' ES have been fundamental in promoting the widespread adoption of sustainable management practices in Colombian coffee cultivation. Scientific advances in plant breeding, integrated pest and disease management, soil conservation, nutrient optimization, and water-efficient processing technologies have provided producers with evidence-based solutions to address productivity, environmental, and market challenges. The integration of these innovations into farm management systems has enabled coffee growers to comply with evolving international sustainability standards while safeguarding nature.

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