Research on World Agricultural Economy
https://journals.nasspublishing.com/index.php/rwae

REVIEW ARTICLE

Agricultural Research in Colombia: Counterpoint with the Brazilian System

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Abstract: This paper analyzes the evolution and structure of Colombia's agricultural research network, paying special attention to the role of government expenditures in modeling this system. The authors also compare the Colombian agricultural network with the path followed by the Brazilian agricultural sector, which has been considered a pattern in South America. For this purpose, a bibliographic review and historical and institutional data are presented. Although agricultural research in Colombia began in the early 20th century, it has evolved more recently with the creation of different public and private institutions linked to the National Science and Technology System. However, agriculture and its research sector have faced major challenges related to government endowments that are needed to fund infrastructure and demand for researchers, as well as lower competitiveness compared to their Brazilian counterparts determined by social profit.

Keywords: Competitiveness; Technological development; Institutions; Social profit

1. Introduction

In most Latin American countries, the agricultural sector is an important source of income and employment. Also, export earnings contribute to overall economic growth, poverty reduction, and the sustainable use of natural resources [1]. Another of the functions attributed to agriculture in the economic development process is the production of food and raw materials to meet the demands of both domestic and foreign markets [2]. This function can be achieved, among other mechanisms, through agri-

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Received: 22 April 2023; **Received in revised form:** 23 May 2023; **Accepted:** 29 May 2023; **Published:** 1 June 2023

Citation: Trujillo, H.A., Bacha, C.J.C., 2023. Agricultural Research in Colombia: Counterpoint with the Brazilian System. *Research on World Agricultural Economy*. 4(2), 848. http://dx.doi.org/10.36956/rwae.v4i2.848

DOI: http://dx.doi.org/10.36956/rwae.v4i2.848

cultural research, which allows the country to expand its range of processed products as well as increase productivity per area. Agricultural research shows up for itself as a proposal for a sectoral approach, fundamentally aimed at benefiting the sector with a view to making it competitive and expanding its capacity to generate profits [3]. However, examining the impacts of research on food systems and, therefore, on farmers and consumers is a complex task.

Agricultural research is considered one of the conditioning factors of agricultural transformation [4], and it has been one of the key factors to explain the increase of agricultural productivity in South America during the last decades, especially in countries such as Brazil, Chile, and Uruguay [5,6]. Producer associations, research foundations, private sector companies, and universities have played an increasing role in the technological development in the region [1]. In turn, increased productivity in agriculture is one of the main sources of growth in the sector [7] and it is associated with greater investment in research in these countries.

Investment in agricultural research is characterized by returns much higher than those obtained in other activities. In the case of Brazil, according to Bonelli and Pessoa [5], rates of return were in the order of 20% to 30% in the first half of the 1990s. More current data, such as the Social Balance of Brazilian Agricultural Research Company (EMBRAPA), estimate an average rate of return on investments in agricultural research of 45.1% [8]. Such investments afforded by the Government expenditures have been beneficial to Brazilian society. At present and by various indicators associated with it, it is evident that Brazilian agriculture has become one of the leading and most competitive in the world. Both the structure and funding of public research in agriculture have been essential to achieving this competitiveness.

Agricultural modernization in Brazil, after the 1960s, was stimulated by government policies at different levels (particularly through rural credit policies, minimum prices, research, and agricultural extension). Innovations in technology (resulting from investments in research) led to an increase in agricultural productivity [5]. In this process, the creation of the National Agricultural Research System (SNPA), the role of EMBRAPA, the role of state-funded research and technical assistance institutions, and the role of universities and private, for-profit and non-profit organizations stand out [9].

In Colombia, agriculture was a determining sector in the country's development during most of the last century, highlighted by the growth of coffee cultivation in different regions [10]. However, since the 2000s, agriculture has decreased its share in the Colombian economy [11,12]. According to data from the World Bank, the National Administrative Department of Statistics (DANE), and the National Planning Department (DNP), the contribution of agriculture to the Colombian GDP went from 25% in 1965 to 22.30% in 1990 and reached only 6.30% in 2017. The loss in the contribution of agriculture and livestock to the Colombian trade balance is the result, on the one hand, of the higher relative growth of other sectors and, on the other hand, of the low productivity of the sector itself. The low productivity of the agricultural sector also generates less development, especially in areas where agriculture has been considered the main economic vocation. During the last three decades, Colombia's economic growth has been driven by the advancement of sectors such as finance, mining, public services, electricity, and information and communication technologies. According to Ludena [13], between 2001 and 2007, the growth rate of Total Factor Productivity (TFP①) in Colombia's agricultural sector declined significantly. This, in part, reflects the lack of a fully structured agricultural research segment that is even capable of being competitive with these other sectors at the national level, as could be the case in Brazil.

Agricultural research in Colombia has progressively advanced and been strengthened with the creation of different institutions and diverse approaches. Agricultural research began systematically in 1914 with the start of academic activities at the School of Tropical Agriculture and Veterinarian of Medellín. At that time, the prevailing view was that agriculture was restricted to the production of food for the domestic market, and there was an enormous need for technical personnel trained in the areas of agriculture, livestock, forestry, fisheries, and natural resources, as well as in post-harvest activities. Although, since the creation of the National Coffee Research Center (CENICAFÉ) in 1938, Colombia had centers specialized in different crops, it was only in 2017 that the National Agricultural Innovation System (SNIA) was established. The main objective of this system is to contribute to the improvement of productivity and competitiveness through the articulation of national and regional policies to encourage the development of science, technology, and innovation in the agricultural sector. Currently, agricultural research in Colombia includes a significant number of governmental entities, higher education institutions, nonprofit, private, and international entities working on it [14]. However, in order to measure, monitor, and compare the resources (human and financial), results, and performance

① Total factor productivity (TFP) can be defined as a ratio of total output to total inputs. Thus, TFP is a unique measure designed to describe the efficiency of the use of inputs to achieve a total volume of final outputs.

of agricultural research and development systems in Colombia over time, it is essential to have indicators that make it possible to evaluate the contribution of agricultural research to the country's development.

In this context, the general objective of this article is to analyze the evolution of agricultural research in Colombia, paying attention to the institutional framework of the public sector, financial and human resources, and the results of the research system, trying to make a comparison with the existing agricultural research system in Brazil. This article is based on a bibliographic survey, the collection of secondary data, and the analysis of technical reports on agricultural research in Colombia and Brazil, comparing them to identify facts that would allow the Colombian system to position itself better in relation to the Brazilian system. In Gil's [15] classification, this is exploratory research using the comparative research method②.

In addition to this introduction, the article comprises five more sections. The second section presents the literature review, placing the previous objective in the context of current knowledge about the subject under analyzing. Section 3 presents the historical milestones of agricultural research in Colombia and Brazil. In sequence, Section 4 presents a comparison between the entities conducting agricultural research in both Colombia and their counterparts in Brazil. Section 5 analyzes the human and financial resources granted to agricultural research in these two countries (Colombia and Brazil), followed by Section 6, which brings the final considerations of the article.

2. Literature Review

The literature closest to this paper's objective refers to works that address the origin and evolution of the agricultural research system and its current stage in Brazil and Colombia. In the case of Brazil, for example, Stumpf-Junior and Balsadi [3] present the historical evolution of Brazilian agricultural research from 1500 until the creation of EMBRAPA in 1973, the different approaches to agricultural research, and an agenda for its development. Considering a more recent period, Castro [16] complements the history and evolution of institutions conducting public agricultural research in Brazil. This author advocates continuing the allocation of public resources to agricultural research because of the results it has achieved. Addressing the situation existing at a given time, there is, for example, the work of Dossa and Segatto [17], who describe the institutions and interrelationships between public and private sector activities in agricultural research in Brazil as they existed in the mid-1990s. They also emphasize the need for the Brazilian government to continue investing in research and in the implementation of new forms of public-private partnerships in order to maximize the social benefits of scientific activity. More recently, Moreira and Teixeira [9] studied the creation of the National Agricultural Research System (SNPA) and development institutions, highlighting the return on investment in agricultural research in Brazil and its impacts on society.

Among the few studies about the agricultural research institutions in Colombia, Roldan [18] provides a historical but not complete panorama. The author starts by highlighting the Botanical Expedition of José Celestino Mutis, emphasizing the various systems of education with a focus on agriculture and livestock. Torres [19], presents a reflection relating to higher education with an agricultural focus in Colombia and the process of creating the Faculty of Agricultural Sciences in the State of Nariño. Recently, Junguito et al. [11] recounted the main problems related to the productivity and competitiveness of Colombian agriculture and have proposed mechanisms for strengthening research institutions, paying particular attention to the Colombian Agricultural Research Corporation (AGROSAVIA), which has come up as the axis of the national system of agricultural science, technology, and innovation.

However, there is a lack of complete studies concerning the evolution of the Colombian agricultural research system, especially about what happened in the first two decades of the 21st century. In this regard, Stads et al. [14] present an analysis of agricultural research institutions in Latin America and the Caribbean (including Colombia and Brazil), detailing the structure and financing of their research systems. However, this work does not highlight how the better performance of some countries (for example, Brazil) can be used as a comparative parameter for other countries, such as Colombia. Given the above explained, the contribution of this article is the registration and analysis of the main historical facts and institutions that allowed the constitution of the agricultural research system in Colombia up to the present time. This comparative analysis with the Brazilian system will make it possible to formulate policy suggestions in Colombia that can meet the demands of its agricultural sector and guarantee its future development.

3. A Historical Survey of Agricultural Research in Colombia and Brazil

The Spanish priest José Celestino Mutis, also a naturalist and mathematician, dedicated himself, after his arrival

② According to Gil [15], exploratory research is developed with the objective of providing an approximate vision of a given fact. On the other hand, the comparative method involves the investigation of individuals, classes, phenomena, or facts in order to highlight the differences and similarities between them.

in Colombia in 1760, to the recognition and study of the Andean flora through several scientific excursions that led to important botanical discoveries. Mutis carried out studies on zoology and minerals, observed astronomical phenomena, and described the geography of the country [20]. During his lifetime in Colombia, Mutis exchanged correspondence with European scholars, especially Mr. Carlos Linnaeus, seeking better cooperation and exchange of knowledge between both scholars about the collection and nomenclature of unknown plants, as well as a scientific development.

In 1805, Francisco José de Caldas assembled a considerable herbarium of species from the southern and southwestern regions of Colombia, recording his observations on the geography and distribution of plants in addition to his contributions to astronomy and physics. This herbarium was an essential component in the knowledge of Colombian plant species not only because of its volume but also because of the descriptions of common uses, especially in agriculture, industry, and the conservation of natural resources in the regions where it was collected.

A century later, in 1914, landmarks were set up for the creation of the School of Tropical Agriculture and Veterinary Medicine in Medellín, and in 1916 its academic activities began. Due to the country lacked of technicians, qualified teachers from the United States of America, Puerto Rico, Cuba, France, and Germany were hired. Four years later, by ordinance, a complete course in agriculture and veterinary medicine was introduced. With the emergence of faculties of agronomy and zootechnics in different Colombian states, there was a great diffusion of new production techniques for different species, which promoted the quality of Colombian agricultural products at the time.

Table 1 displays the main historical milestones in the process of creating agricultural science research and education institutions in Colombia. From the 1940s to the 1960s, several faculties were created to provide undergraduate courses in agricultural sciences. The 1970s and 1980s were characterized by the creation of several research centers focused on specific agricultural activities. Since its creation in 1970, the Faculty of Agricultural Sciences at the Universidad Nacional de Colombia in Palmira has pointed out among the most relevant public institutions that provide higher education in the country, with an emphasis on agricultural sciences. This institution has contributed to the generation and development of research in agronomy, biotechnology, agricultural innovation, environment, biodiversity, and zootechnics, not only for the Valle del Cauca region, which is an important Colombian agricultural region, but also for the development of other Andean and Pacific Colombian regions.

Later, with the creation of the Colombian Agricultural Research Corporation (AGROSAVIA) in 1993, national public research began to be centered in this institution, which became responsible for generating scientific knowledge and technological solutions through research, innovation, technology transfer, and the training of researchers for the benefit of the Colombian agricultural sector. Together with the Faculty of Agricultural Sciences of the Universidad Nacional de Colombia in Palmira and the International Center for Tropical Agriculture (CIAT), both placed in the same region, they form the hub of agricultural research in Colombia. In addition, the institutional framework stimulates the strengthening of the former National Science and Technology System and its definition. Law 607, issued in 2000, has modified the creation, functioning, and operation of the Municipal Agricultural Technical Assistance Units (UMATA) and regulated direct rural technical assistance. Those have turned viable, the participation of the territories in technological activities. In this path, the implementation of the Strategic Plans for Science, Technology, and Innovation (PECTIA) formulated for most of the country's states has been noble.

Brazil, from 1808, when the Rio de Janeiro's Botanical Garden was inaugurated, to 1973, when EMBRAPA was founded, has faced several swings between federal and state institutions in conducting activities linked to the generation of science (knowledge) and technology (processes and products) oriented to the development of Brazilian agriculture. Public agricultural research was greatly strengthened with the creation of the Agronomic Institute of Campinas (IAC), an agency of the State of São Paulo since the beginning of the 20th century, but which was originally established in 1887 by the Central Government (at that time it was an Imperial Government) as the Imperial Agronomic Station of Campinas.

In Brazil, the State of São Paulo headed the Brazilian agricultural research from the beginning of the 20th century until the end of the 1970s. Agronomic Institute of Campinas (IAC), the Biological Institute (IB), and the Zootechnical Institute (IZ), which concentrated on Brazilian agricultural research during the first three decades of the 20th century were later, joined by four other state institutions (Institute of Agricultural Economics (IEA), Institute of Food Technology (ITAL), and Institute of Fisheries and Forestry (IF)) [21]. The emergence of formal postgraduate degrees *stricto sensu* courses, in mid-1960s, allowed public universities (federal and state) to conduct an important share of agricultural research in Brazil [3]. Brazilian public model of agricultural research fells strongly on Government funding, which includes the con-

Table 1. Landmarks the evolution of agricultural research institutions in Colombia.

Year	Landmark
1914	Creation of the School of Tropical Agriculture and Veterinary Medicine in Medellin, later named the National Agricultural Institute
1930	Start of the sugarcane program at the Experimental Station of the Colombian Agricultural Institute (ICA) in Palmira
1934	Creation of the Agricultural Institute of Valle del Cauca (later as Escuela Superior de Agricultura Tropical del Valle del Cauca (ESAT)), the Experimental Agricultural Farm of Palmira, and the Agricultural Extension Service of the State
1938	The National Agricultural Institute merged with the National University of Colombia, was renamed the National Faculty of Agronomy, later named the Faculty of Agricultural Sciences, and is currently the Faculty of Agricultural Sciences in Medellin Creation of the National Coffee Research Center (CENICAFÉ)
1940	Sugar mills-initiated research and experimentation activities and later, starting in 1955, established cooperation agreements with the ICA sugarcane program
1943	The Faculty of Agronomy is created, linked to the Universidad Popular de Manizales, currently the Universidad de Caldas
1944	ESAT became Faculty of Agronomy of Valle del Cauca
1945	The Faculty of Agronomy of Valle del Cauca was incorporated into the Universidad Industrial del Valle del Cauca and became the Faculty of Agronomy of the Universidad Industrial del Valle del Cauca
1946	The Faculty of Agronomy of the Universidad Industrial del Valle del Cauca joined the Universidad Nacional de Colombia: Facultad Nacional de Agronomía - Palmira Creation of the Faculty of Agronomy of the Universidad de Nariño
1955	Creation of the University of Tolima as a Faculty of Agronomy
1963	Creation of the Faculty of Agronomy of the National University of Colombia in Bogotá
1963	Inauguration of the tropical research center that later became the Marine and Coastal Research Institute (INVEMAR)
1967	Establishment of the International Center for Tropical Agriculture (CIAT) in Palmira
1970	The National Faculty of Agronomy in Palmira becomes the Faculty of Agricultural Sciences, Palmira Campus, of the National University of Colombia
1974	Creation of the National Corporation for Forestry Research and Development (CNRF)
1977	Creation of the National Sugarcane Research Center (CENICAÑA)
1985	Creation of the Banana Research Center (CENIBANANO)
1986	CIMPA: Research Agreement for the Improvement of Panela, signed between the Governments of Colombia and the Netherlands (Dutch Cooperation)
1990	Establishment of the National Oil Palm Research Center (CENIPALMA)
1993	Creation of the Colombian Agricultural Research Corporation (CORPOICA), transformed in May 2018 into AGROSAVIA
1993	Creation of the Colombian Center for Aquaculture Research (CENIACUA)
2003	Creation of CENIRED, composed of research and development centers: CENIACUA, CENIBANANO, CENICAFÉ, CENICAÑA, CENICEL, CENIFLORES, CENIPALMA and CONIF
2004	Creation of the Colombian Center for Innovation in Floriculture (CENIFLORES)
2012	Creation of the Cereal and Vegetable Research Center—CENICEL
2015	Creation of Science, Technology, and Agricultural Innovation Parks, Law 1753 of 2015

Source: Prepared by the authors based on the historical references of each institution.

struction of buildings, the installation of laboratories, and, above all, the training of competent researchers' teams as well as professors at worldwide highest ranked universities [16]. Embrapa, linked to the Ministry of Agriculture, Livestock, and Supply (MAPA), has been, since its creation, responsible for generating, by itself or jointly with other agencies, new agricultural knowledge and technologies for the country. Along with the creation of Embrapa

came the stimulus for the creation of other institutions at the state level in different regions. All together assemble the National Agricultural Research System (SNPA), currently in force. The current structure of Brazilian agricultural research is made up of public and private institutions and a higher education system with an outstanding degree of experience and performance, which has created a consolidated system in Latin America and has provided important contributions to Brazilian agriculture growth.

4. Main Entities that Carry out Agricultural Research in Colombia and Brazil

Works such as those by Dossa and Segatto [17] draw attention to the four groups of organizations that carry agricultural research in Brazil: Embrapa (linked to the Federal Government), state public agencies (in the form of autarchies and/or state-owned companies), universities (especially the state-funded universities), and private companies. This item aims to evaluate the paths by which these organizations play in Colombia and contrast them with those that exist in Brazil.

According to Stads et al. [14], until 2013, 40% of the agricultural research carried out in Colombia was done by state-funded agencies, 20% led by the universities, and 40% by private sector entities and/or mixed-law organizations (private and public). For comparative purposes, in Brazil, in the same period, this distribution was 73%, 25%, and 2%, respectively. These data already illustrate, at least, that the aforementioned entities play different roles in the conduct of agricultural research in the two countries analyzed (Colombia and Brazil).

4.1 Public Institutions Conducting Agricultural Research: Agrosavia in Colombia versus Embrapa in Brazil

Among the entities with government participation dedicated to agricultural research in Colombia, Agrosavia is the largest. It is a public, decentralized, non-profit institution (in a similar mold to Embrapa). Its main function is the generation of scientific knowledge and the development of agricultural technologies through research, adaptation, transfer of technology, and technical assistance. Agrosavia has 21 research units, of which 13 are centers and 8 are headquarters located in different agricultural regions of the country (Table 2). These units carry out research related to permanent crops (cacao and citrus, for example), transition and agroindustry crops, fruit trees, livestock, other crops, vegetables, and aromatic plants.

Table 2. Comparison between AGROSAVIA in Colombia and EMBRAPA in Brazil by number and type of researchers, research centers, laboratories, portfolio, and social benefit for 2019.

	AGROSAVIA	EMBRAPA
Year of foundation	1993	1973
Indicators		
Total number of researchers	378	2,252
Researchers with Master Degrees	211	236
Researchers with PhD Degrees	143	1,704
Other researchers[A]	24	312
Research centers[B]	21	50
Total number of laboratories	49	600
Portfolio	7	34
Social balance sheet		
Technologies analyzed	26	160
Developed crops	n.d.	220
Corporate shares	4	n.d.
Social profit (USD $, currency in 2020)		
Social profit ($USD)	$120,449,575.77	$6,695,523,028.94

Source: Prepared by the authors based on Agrosavia 2019 social report [22] and Embrapa 2019 social report [23].
Notes: [A] In the case of Agrosavia, professionals linked to research are included; in the case of Embrapa postdoctoral researchers are included. [B] In the case of Agrosavia there are 13 research centers and 8 headquarters; in the case of Embrapa, there are 43 decentralized units and 7 central units.

Agrosavia also generates knowledge on the conservation and sustainable use of biodiversity [20].

According to Table 2, researchers with Ph.D. and Master's degrees linked to Agrosavia in 2019 represented 38% and 56%, respectively, of the total. In 2013, according to Stads et al. [24], the participation of PhDs and Masters in the same institution was 15% and 17%, respectively. Despite the relative improvement in the linkage of high-level personnel during the last decade, previous years were characterized by lower paid salaries in the public sector combined with inefficient job promotion inside the public research system, which led many scientists to seek other better-paid positions, even abroad. While the increase in the number of researchers with doctoral and master's degrees has been significant in Colombia over the last decade, attracting highly qualified researchers in some priority areas remains a challenge for agricultural research in Colombia.

In 2019, the social return of the investments in agricultural science and technology in Colombia, considering the case of Agrosavia, was 2.15 for each monetary unit invested (1:2.15). That is, for every Colombian peso (COP) invested, COP$ 2.15 was generated in benefits for the sector. The total social benefit of Agrosavia in 2019 was USD$ 120,449,575.77, which comes from the 26 technologies analyzed, 4 corporate actions, and also includes plant and animal genetic material, crop management recommendations, different types of protocols for production, agricultural designs, agroindustry, and extension [22]. These technologies enabled the improvement of production systems in different regions of the country.

As mentioned, public agricultural research in Brazil is carried out at the federal and state levels. The Embrapa is the main federal entity in Brazil, with at least 50 research centers spread over all regions and a team comprised of 2252 researchers, 76% of whom have PhDs degrees (Table 2). In Brazil, the Dominican Republic, Ecuador, Panama, and Venezuela, the government sector hired more than 70% of agricultural researchers in each country [14]. Embrapa agricultural research spectrum is also quite broad, covering at least 34③ knowledge fields. In addition to Embrapa's involvement, most Brazilian states have their own agricultural research entities focused on their state realities. In Brazil, Embrapa (together with state public institutions and public universities) generated knowledge and technologies for national agriculture, which enabled the reduction in production costs and helped the country increase the food supply in a sustainable manner, in addition to reducing the value of the basic food basket by more than 41.49% [23]. The social return for each Brazilian monetary unit (Reais) invested in Embrapa in 2019 was R$ 12.29 (1:12.29), which came back to the Brazilian society in the form of technologies, knowledge, and employment. Embrapa generated in the country, in 2019, a social return of USD$ 6,695,523,028.94, calculated from the economic impacts of a sample of 160 technologies and about 220 cultivars developed by the research company and its partners [23], showing its high efficiency and consolidation in the exercise of agricultural research.

4.2 Regional Research and International Cooperation

Colombia has some regional organizations that conduct agricultural research, and several of them hold cooperation with other organizations inside Latin America and the Caribbean (LAC). Among them is the Inter-American Institute for Cooperation on Agriculture (IICA), which plays a useful role in coordinating, promoting, and facilitating sustainable agricultural development in the region. IICA works with all the LAC countries as well as with several centers of the Consultative Group on International Agricultural Research (CGIAR) and other regional organizations. The CGIAR Consortium conducts most of the international research in the LAC region. It participates in agricultural research and development in the region through three centers, including the International Center for Tropical Agriculture (CIAT) in Colombia.

At the same time, the Agricultural Research Cooperative Programs (PROCIs) comprise a series of sub-regional mechanisms made up of a group of national agricultural research institutes. The PROCIs focus on the development and strengthening of institutions, the coordination of research projects in several countries, and the promotion and transfer of technology. Currently, there are four programs running: PROCISUR (Argentina, Bolivia, Brazil, Chile, Paraguay, and Uruguay); PROCITROPICOS (Brazil, Bolivia, Colombia, Ecuador, Peru, Suriname, and Venezuela); PROCIANDINO (Bolivia, Colombia, Ecuador, Peru, and Venezuela); and PROCICARIBE (Caribbean) [25]. On the other hand, the Tropical Agricultural Teaching and Research Center (CATIE) is an autonomous non-profit institution focused on agricultural and rural development and natural resource management. Member states include Colombia, where research on rural communities and so-

③ They include: irrigated agriculture, food, Amazon biosystem, aquaculture, automation, precision and digital agriculture, advanced biotechnology applied to agribusiness, cocoa, coffee, meat, drought in the semi-arid region, energy, chemistry and biomass, fibers and biomass for industrial use, forestry, temperate fruit growing, tropical fruit growing, grains, vegetables, organizational innovation, social innovation in agriculture, biological inputs, livestock and forestry integration, intelligence systems, land management and monitoring, milk, rational pesticide management, climate change, nanotechnology, agricultural nutrition, pastures, genetic resources, animal health, plant health, environmental services, ecologically based production systems and Brazilian soils.

cial welfare is carried out.

4.3 The Role of Universities in Agricultural Research in Colombia Compared to Brazil

In the 1940s, 1950s, and 1960s, several faculties of agronomy were created in Colombia, spreading higher education about agricultural sciences over different regions (Table 1). The 1960s also saw the creation of several agricultural research centers, formalizing the creation of the Colombian Agricultural Institute (ICA), formerly the Department of Agricultural Research (DIA) [19]. The Agricultural Institutes (ITA) played a role in modernization and technology transfer, but this modernization was not the result of an analysis of the cultural, economic, and social conditions of the existing agricultural sector at that time but was driven by the need to reach international standards [26]. In the 1970s, under the influence of the new global trends, intermediate-level agricultural training programs were created. This step constitutes the main measure of the modernization of agricultural education in Colombia, which promoted training at the technical level, the updating of higher education, and training in institutions.

In line with the promotion of agricultural education, academic programs were created in Colombia that are still running today (Tables 1 and 3), including the public programs of the Universidad Nacional de Colombia in Palmira, Medellin, and Bogota, the Universidad de Caldas, the Universidad del Tolima, and the Universidad de Nariño. These public institutions stand out in the generation of scientific knowledge and technologies, contributing to the development of agriculture.

According to data from the SNIES [28], in 2019, there were at least 73 higher education institutions, public or private, with programs related to agricultural sciences in Colombia. In general, for this period, the number of public institutions is greater than that of private institutions; however, the latter has a greater number of courses dedicated to the teaching of agricultural sciences at the undergraduate level (Table 3), which evidences that the Colombian educational system, as far as agricultural sciences are concerned, is determined by the growing participation of the private sector. Although the Colombian educational system has both public and private representation, public institutions of higher education, as in other LAC countries, should play a major role in agricultural research in Colombia. However, according to Triana [26], Colombian public education faces greater challenges related to central government management, which has demonstrated an inability to adequately provide the right to education in terms of coverage, quality, and financing, which directly affects investments in research and the development of this sector.

In terms of the number of students enrolled and graduates in agricultural sciences courses, in 2019, Colombia reached only 2% of the total number of students enrolled in the country, while the percentage of graduates in this area was 1.6%. In Brazil, these percentages were 3.2% and 2.5%, respectively (Table 3). The punctual and con-

Table 3. Comparison of education systems in agricultural sciences between Colombia and Brazil, considering the year 2019.

Year 2019	Colombia		Brazil	
	Private sector	Public sector	Private sector	Public sector
Institutions with programs in agricultural sciences [A]	33	40	377	144
Undergraduate courses in agricultural sciences	51	44	610	630
Students enrolled in the country by sector [B]	1,178,120	1,218,130	6,523,678	2,080,146
Students enrolled by sector/percentage of total (%)	49	51	76	24
Total students enrolled in the country	2,396,250		8,603,824	
Students enrolled/agricultural programs	49,292		141,438	130,591
Total number of graduates in the country	507,338		1,250,076	
Graduates of agricultural science programs	8,275		16,664	15,246

Source: Prepared by the authors based on the National Information System for Higher Education in Colombia (SNIES) [27,28]. and the National Institute of Educational Studies and Research Anísio Teixeira (INEP) [29].

Notes: [A] In the case of Colombia, this includes institutions with agronomy, veterinary, and related programs. In the case of Brazil, this includes institutions with programs in agriculture, forestry, fisheries, and veterinary science. [B] In the case of Colombia, this includes undergraduate (university), professional technical, technological, master's, and specialization courses. In the case of Brazil, it includes *stricto sensu* and *lato sensu* undergraduate courses by administrative category in different areas.

centrated geographic location of educational institutions has been highlighted as a central factor that does not make it possible to alleviate the technological and economic lags in a significant part of the Colombian agricultural sector [30]. In addition, for more than 30 years, Colombia has not created a new public university or college, much less one dedicated to agricultural sciences. Therefore, there is a need for greater territorial coverage of the teaching offered in agricultural sciences, especially in regions with high productive potential where agriculture and livestock represent the main engines of economic development.

The public share of higher education in agricultural sciences in Brazil also plays a recognized and important role, with more than 144 units linked to public universities (federal and state) and federal institutes of education, science, and technology, offering courses in several different modalities of the agricultural sciences and training a lot of professionals to work in the different fields of agriculture and development. According to INEP [29], in 2019, Brazil had 521 undergraduate and graduate courses in agricultural sciences evaluated and recognized by the Ministry of Education and Culture (MEC). Despite there being higher education courses linked to agricultural sciences throughout the country, there is a concentration of them mainly in the Southeast, South, and Northeast regions.

4.4 Agricultural Research Conducted by the Private Sector

According to Bonelli and Pessoa [5], a large share of agricultural technology is considered a public patrimony; therefore, it is mainly generated by government-owned research institutions, which benefits society, although it does not generate a direct financial return for the entity generating these new technologies. However, when it is carried out by profit-oriented institutions, there is a tendency to privatize and reduce the resources allocated to this activity. This justifies, in the case of Brazil, the relatively small participation of the private sector in running agricultural research (Tables 3 and 4). But this is not the case in Colombia, where the private entities that carry out agricultural research do not necessarily have as a principle to maximize their profits but rather the profit of specific sectors. This makes private, profit-oriented agricultural research relatively important in Colombia compared to other South American countries [14]. In many cases, agricultural technologies reach degrees of specialization and have private input supply, processing, harvesting, and post-harvest systems. Some countries offer tax exemptions for private research, and many require their participation in publicly funded projects as a mechanism to promote the commercial viability of the results generated by the research. Many private companies also make their research results available to universities or government agencies, or import technologies from abroad [31]. Since the creation of CENICAFÉ—which was created in the late 1930s—several agricultural production corporations in Colombia have, over time, become aware of the need to invest in research to improve productivity and ensure the competitiveness of their activities. Therefore, they have created their own research centers, called National Research Centers (CENI), such as CENIACUA, CENIBANANO, CENICAÑA, CENICEL, CENIFLORES, CENIPALMA, and CONIF. These centers are mainly financed by the private sector. The CENIs have been an important tool in the economic development of the agricultural sectors they represent in the country [32]. These entities have sought to promote the development and modernization of the agricultural sector, especially those sectors with the greatest potential (in the case of large crops). Since 2003, the CENIs have congregated under an umbrella corporation called CENIRED, which facilitates the exchange of scientific and technological advances and resources among the main sectors: Agroforestry, bananas, coffee, shrimp, sugarcane, flowers, cereals, legumes, and oil palm [32]. Although this corporation groups the most important research centers in the country, each center has its own mission. However, they all have focused their efforts on the competitiveness and strengthening of their sector in order to contribute to its economy and development.

5. Financial and Human Resources Allocated to Agricultural Research in Colombia and Brazil

According to data from Stads et al. [14], financial amounts in agricultural research and development in Colombia and Brazil (excluding the private non-profit sector) were subject to considerable volatility during the 1980s and early 1990s. This was followed by a period of steady decline until the early 2000s.

For Brazil, after a period of strong growth, the total capacity to link researchers to agricultural technology development varied sharply, mainly during the years 1990-2004. The growth of this capacity in recent years resulted from greater participation in agricultural research by the higher education sector and the opening of new Embrapa centers in different Brazilian states, which increased the number of researchers hired. As a result, investment levels also increased from 2005 onward. From 2009 to 2013, the country invested US$ 2,704 million in research linked to the agricultural sector, which represents at least half of the total expenditure in the LAC region in this category [14,33]. Therefore, Brazil figures as the most important country in

LAC in terms of spending on agricultural research. According to this same study, Colombia topped the list of the top five countries in investment in agricultural research from 2009 to 2013, with an investment of close to US$ 253 million.

Table 4 shows the distribution of spending on agricultural research in Colombia and Brazil from 2009 to 2013, highlighting items such as net spending, growth in spending, researchers assigned, and the participation of different sectors in research in 2019.

The data in Table 4 show that agricultural research spending in Colombia was at least 10 times lower than in Brazil. Moreover, Colombia's agricultural GDP (in 2019) was 5 times lower than Brazil's (according to World Bank data), proportionally. In 2013, public investment in agricultural research in Colombia corresponded to 0.79% of its agricultural GDP, while in Brazil this percentage was 1.82%. The most developed countries invest about 4% of their agricultural GDP in agricultural research, while the least developed countries invest around 1%. Therefore, Colombia's total investment in agricultural research is relatively lower than that of Brazil.

Colombia is less competitive than Brazil in terms of both the number of researchers involved and the percentage of PhDs among researchers conducting research in the agricultural sector. Only 23% of researchers related to agriculture and livestock had a Ph.D. degree in Colombia, compared to 73% in the Brazilian case, considering the

Table 4. Financial and human resources linked to agricultural research activities in Colombia and Brazil from 2009 to 2013, participation of sectors in research, and operating income in 2019.

ITEM	Colombia	Brazil
Expense		
Research expenses in millions of dollars (USD $) [A]	253	2,704
Growth of the sector [B]	33.3%	7.8%
Percentage of agricultural GDP [C]	0.79%	1.82%
Researchers		
Number of full-time equivalent researchers [D]	1,102	5,869
Growth of the sector [E]	2.95	11.5%
Percentage of researchers with a doctorate degree [F]	23%	73%
Financing sources		
Public participation (Agrosavia and Embrapa)	90%	97%
Donations and Development Banks	1%	1%
Sales of goods and services	9%	2%
Public participation in agricultural research		
Public participation (Agrosavia and Embrapa)	29%	42%
Non-profit and for-profit organizations	12%	1%
Operating Income 2019 (USD $)		
Net operating income (Agrosavia and Embrapa)	$55,859,765.38	$545,006,368.92

Source: Prepared by the authors based on STADS et al. [14] and ASTI [25].

Notes: [A] Total agricultural research spending includes salaries, operating and program costs, and capital investments for all higher education agencies, nonprofit institutions, and government entities conducting agricultural research activities (excluding the private sector) in the country in the period 2009 through 2013. [B] Expenditure growth includes increases in salary costs, program costs, and operating and capital investments in all public, non-profit, and higher education entities (excluding the private sector) that carry out agricultural research activities in the country. [C] Percentage of investment in agricultural research (total research expenditure excluding the private for-profit sector as a percentage of agricultural GDP). [D] The total number of agricultural researchers in the public sector includes all researchers working in government, non-profit organizations, and higher education (excluding the private sector). The data are expressed in full-time equivalents (FTE). [E] The increase in the total number of agricultural researchers in the public sector includes all researchers working in government, organizations, nonprofit organizations, and higher education (excluding the private sector). The data are expressed as a percentage of full-time employees (FTE). [F] This indicator reflects the number of agricultural researchers with a Ph.D. as a percentage of the total number of agricultural researchers in the public sector (with Ph.D., MSc., and undergraduate degrees).

years from 2009 to 2013. In general, the number of scientists with a Ph.D. degree is considered fundamental for the conception and implementation of high-quality research programs, to establish efficient communication with policymakers, donors, and other actors, both locally and in regional and international forums, as well as to increase the opportunities for institutions to obtain more resources for their activities [25].

Financial resources for agricultural research in Colombia and Brazil come from various sources, including the national government, international donors, development banks, producer organizations, and other private sector agents. In addition to income generated by the research institutions themselves through the sale of goods and/or services.

Regarding the budget, until 2013, Agrosavia was financed by the Ministry of Agriculture through technical cooperation and contracts, but since the enactment of Law 1731 of 2014, there is a national budget line within the budget approved by Congress, and resources are channeled to Agrosavia through the Ministry of Agriculture. For 2019, this budget was USD$ 55,859,765.38 (Table 4). Despite the budget had increased in recent years, total amount disbursed with agricultural research in Colombia is relatively lower when it is compared to other countries located in the same region [24]. In most Agrosavia centers, more funding could contribute to salary increases and related operating expenses. Therefore, capital investment is vital to meet the demands for infrastructure, technology acquisition, and transfer.

The federal government's financial support for agricultural research in Brazil, despite oscillating since the 1980s [34], has enabled Embrapa's important performance in South America, its partnerships, and international cooperation. For 2019, Embrapa's operating budget was USD$ 545,006,368.92 (Table 4). The participation of the public sector in the financing of agricultural research institutions in Brazil is much more significant than in Colombia. However, according to Stads et al. [24], with the economic slowdown and crisis, there is uncertainty about possible cuts in future budgets that could restrict the activities of agricultural research agencies in Brazil.

In Colombia, Agrosavia's main source of funding is the central government. Although this participation is high (percentage), there is a tendency to increase the sale of products and services to access new resources, which may lead this institution to become less dependent on the government in the future. This same trend can be observed in the participation of other Colombian institutions related to agricultural research activities. However, it is necessary to observe the trend in this aspect over time up to the present day.

Since agricultural research is a typical public good with benefits for the whole society, the state should provide a very high share of the funds for this activity. Leaving the function of financing research to private agents and sectoral funds will represent a future threat to the system since the volume and type of research would be below what is socially necessary, even when financed with parafiscal contributions, as has been the case in Colombia [11]. One strategy to promote agricultural development in specific regions by providing them with scientific and technological capacity to meet their own demands is to create regional agricultural research and innovation systems, such as those existing in Brazil. In Colombia, the model is configured to meet the demands of particular sectors, as in the case of the CENIs, and not regional demands.

Due to the importance that has been attributed to specific sectors of primary production, there is a trend in the distribution and execution of research in each country. In Colombia, 59% of agricultural research is devoted to major crops (including coffee, sugar cane, and fruit production, for example), 9% to livestock (including meat and milk production), 17% to the management and preservation of natural resources, 0.5% to forestry, 1% to fisheries, and 13.5% to other agricultural activities. For Brazil, major crops account for at least 72% of agricultural research (highlighting coffee, citrus, soybean, corn, sugarcane, cotton, non-citrus fruits, and other oilseed species); livestock 9% (milk and meat); natural resource management and preservation 3%; forestry 1%; fisheries 2%; and other agricultural activities 13% [14,24]. This distribution in the focus of agricultural research is linked to the sectors in which each country has achieved greater competitiveness, not only in the domestic market but also in its exports and, consequently, in the generation of foreign exchange.

Another challenge has to do with the level of public funding needed to ensure effective strategic research programs that generate greater agricultural productivity. The trend towards the restriction of public spending on agricultural research has led research entities to have limited options for obtaining resources, and the allocation of these resources is increasingly scarce [30,31], especially in countries such as Colombia, where state policies have not considered this component a priority for national development. According to Stads et al. [14], it is essential that governments provide the necessary political environment to foster cooperation among agricultural research entities in their countries in order to maximize synergies between universities and government entities and efficiencies in the use of available resources. In the Colombian case, it is important to consider exogenous factors that from the

national context have limited investment in research, such as the allocation of the national budget to other portfolios with the idea of responding to the internal armed conflict by the governments in power, the variation of the exchange rate that discouraged exports, the discouragement of the sector in the face of the economic opening since the end of the 1990s, and the high cost of the fight against drugs due to the increase in crops destined for illicit uses.

6. Final Remarks

Agriculture is a dynamic activity in which several factors and components converge to make its development possible. Apart from the inputs of credit, labor, and market to be done, it is also necessary to generate new knowledge and technology to allow it to be developed. Both knowledge and technology are generated thanks to the research programs carried out by institutions, and they have a huge impact on the country's overall agricultural competitiveness. As shown throughout the paper, the research system for the generation of agricultural science and technology in Brazil is predominantly public, and the federal entity (Embrapa), which includes regional features, forms a network together with institutions of higher education (federal and state universities) and state research institutions. This model of a public-funded agricultural research network in Brazil (despite its irregular allocation of resources) has generated important results, especially because the agricultural technology that they generate is difficult to privately register and is freely spread, which has had a great impact on Brazilian agricultural productivity.

Colombian agriculture has faced a decrease in productivity that has led to a loss of competitiveness in this sector. Federal-funded Agrosavia's research has generated a lower return to Colombia than similar Embrapa's research has turned back to Brazil. However, greater investments in financial resources and human capital are considered necessary for the development of more efficient agricultural research programs in Colombia. This stands out as the greatest challenge to be overcome, especially in recent years. Complementing this, there is a need to structure a research system that can meet regional demands more efficiently in all agricultural sectors in Colombia. This will require an even stronger link with agricultural research on the part of higher education institutions, especially public institutions that, in turn, demand greater investment, coverage, and capacity to train highly competent professionals in different fields that compound the agriculture sector.

Author Contributions

Heiber Andres Trujillo: Study conception and design, data collection, analysis and interpretation, elaboration of the text (different versions), critical revision of the article with important contributions to its intellectual content, approval of the final version to be submitted. Carlos José Caetano Bacha: Study conception and design, critical revision of the article with important contributions to its intellectual content, approval of the final version to be submitted.

Acknowledgement

Acknowledgement to the 'Doctorado Exterior—885' program of the 'Ministerio de Ciencia Tecnología e Innovación (MINCIENCIAS) Colombia' for funding since 2021. To the 'PROEX' program of 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Brazil' for the scholarship.

Data Availability

The data are available upon request from the corresponding author.

Conflict of Interest

All authors disclosed no any conflict of interest.

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