

Review

# Scientific Research on Bioethanol in Brazil: History and Prospects for Sustainable Biofuel

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**Abstract:** Despite the recent need for sustainable energy resources, bioenergy gained its spotlight in the 2000s. Sugarcane is a significant crop in terms of sugar and energy capacity, and it can be an alternative energy source to mitigate the effects of climate change. Bioenergy production from sugarcane in Brazil is one of the most efficient options. This production lends a centrality to biofuels' importance in confronting climate change effects. The present article reviews the Brazilian history of this crop as a biofuel source, focusing on plants as a biomass. We highlight the historical changes related to scientific, technological, industrial, and environmental advances since the beginning of the 20th century. We describe how creating governmental institutes and disseminating scientific knowledge strengthened public policies that led Brazil to occupy leadership positions in producing, distributing, and using bioenergy throughout the country. The compiled data show the improvements and the new approaches needed to improve ethanol sugarcane use. We performed a bibliometric analysis to evaluate Brazilian science's contribution to this process compared to other countries. Brazil's history of science and investment in sugarcane biofuel development for transportation may be divided into two phases: ethanol-only and flex-fuel cars. A third phase is starting, directed to the SAF and ethanol-to-hydrogen era.

**Keywords:** biomass; alcohol; development; science investments; bibliometrics; green energies



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## 1. Introduction

Bioenergy can be defined as all energy forms associated with photosynthesis [1,2], including biomass, which has been known about and used since the Paleolithic era (2,500,000 years–10,000 years B.C.) for cooking, heating, and lighting [3,4]. The burning of wood was sufficient to produce heat and light until the Industrial Revolution (1760 A.C.), when fossil energy sources (i.e., oil, mineral coal, and natural gas) became 80–84% of the total world energy supply [5,6]. However, these non-renewable energy sources are scarce, estimated to last 57 years (oil), 49 years (natural gas), and 139 years (coal) [7]. This scenario raised the need for new matrices and the conversion of biomass to electricity (gasification and pyrolysis) and liquid fuels (bioethanol, biodiesel, and bio-oil from pyrolysis) [8].

Annual biomass storage amounts to three to four times the current global energy demand, representing a sustainable substitute for oil derivatives [3]. Energy crops will be responsible for 30% of the energy required worldwide by 2050 [3]. Therefore, these crops must have high yield, low energy consumption, a high content of compounds of interest (starch, sugars, and lipids), few polluting chemicals, and low nutritional requirements [9].

In this context, the Brazilian sugarcane bioethanol production system is the most efficient [5,10]. Brazil is the largest sugarcane producer (accounts for approximately 46% of the sugarcane production worldwide [11], with 715.7 million tons (2020/2021 harvest), generating 32 billion liters of ethanol (2020/2021 harvest) [12]. India, China, and Pakistan

occupy the second (405 million tons (2021), third (107 million tons—2021), and fourth (88 million tons) positions in the sugarcane production rank, respectively [11]. Here, we review the history of sugarcane and ethanol production in Brazil, focusing on plant biology as a biomass source to improve bioethanol from sucrose (1G) and cellulose (2G), examining the scientific, technological, industrial, and environmental advances from the beginning of the 20th century, along with a bibliometric evaluation of the contribution of Brazilian universities in this process.

## 2. History of Ethanol Production from Sugarcane

Sugarcane's first description dates to 500 B.C., in Indian manuscripts [13], but only in 1793 was it classified as *Saccharum* by Linnaeus [14]. The relatively high sugar accumulation spread the global interest in sugarcane. Sugarcane's route started in China, and then it entered the Middle East, was introduced to Egypt and Greece by Arab populations, arrived in the Roman Empire through Sicily, and then reached the Americas [13]. Initially, sugarcane was used for medical purposes in India and China as a natural juice and sweet syrup. Later, sugarcane syrup began to be used as a sweetener in beverages. Portugal and Spain dominated sugar technology, with plantations in the Atlantic Islands and Central and South America. Cachaça, a kind of rum, was developed in Brazil by enslaved people through cane juice fermentation, followed by distillation, and it became popular in 1776 [13].

Alcohol as a fuel was tested in 1826 by the American Samuel Morey in an internal combustion engine, where it was combined with turpentine to operate a boat [3]. The German Nicolaus August Otto developed another engine that worked with a mixture of ethanol and gasoline, and Henry Ford built tractors that could run only on ethanol [15]. The capacity and sustainability of alcohol were defended by many scientists when gasoline took over the market in the 1910s [3]. In 1917, Alexander Graham Bell highlighted the abundance of raw plant materials that could be used for producing ethanol. In 1918, an article in *Scientific American* showed the efficiency of a fuel consisting of 25% gasoline, 25% benzol, and 50% alcohol, proposing it as a solution to the high consumption of oil reserves [15].

In Brazil, infrastructure for alcohol production for the automotive and other industry sectors was discussed and planned at the First National Congress on the Industrial Applications of Alcohol in 1903 [16,17]. In 1920, the Experimental Station of Fuels and Minerals (*Estação Experimental de Combustíveis e Minérios*), which later became the National Institute of Technology (*Instituto Nacional de Tecnologia—INT*), was created to test alcohol-powered vehicles (called alcohol-motor), and in 1931, 5% anhydrous ethanol was added to gasoline to reduce oil use [16,18].

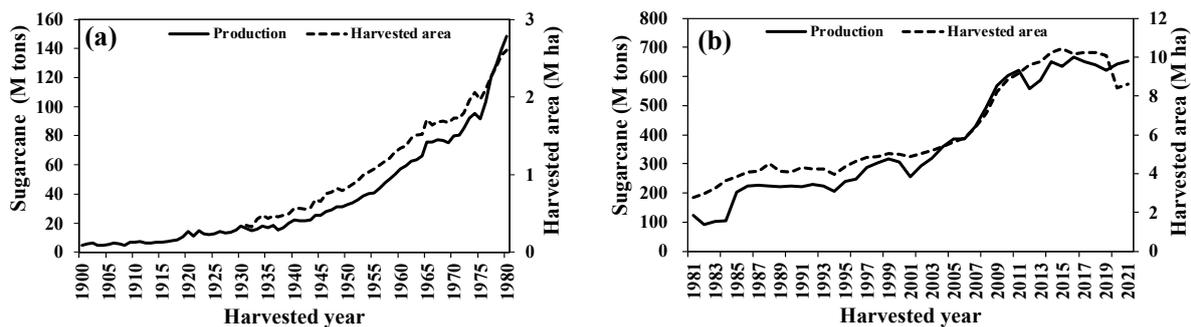
Henry Ford developed flexible-fuel technology for cars in the United States of America (USA) in 1908, and General Motors launched it commercially in 1992 [19]. Those engines worked with gasoline or E85 (ethanol with 15% gasoline) [20], but not with pure ethanol. Brazil pioneered the selling of ethanol-powered vehicles, developing a large fleet of flex-fuel cars, and the government has been increasingly adding ethanol to gasoline for several decades, reaching 27%, to minimize carbon emissions into the atmosphere [13]. Only in 2003 did other countries begin regularly adding ethanol to gasoline, but at lower proportions (5–10%) [21].

## 3. Foundation of the Institutions and the First Investments in Sugarcane Agriculture in Brazil

Starting in 1500 with the arrival of the Portuguese in Brazil, sugarcane plants began to be cultivated mainly in the northeastern region, at first, which lasted up to the 20th century. The emperor Dom Pedro II ordered the creation of several agricultural institutes [*Instituto Imperial Bahiano de Agricultura* (1859), *Instituto de Pernambuco* (1859), *Instituto de Sergipe* (1859), *Instituto Fluminense* (1860), and *Instituto do Rio Grande do Sul* (1861)] across the country to boost national products and promote sugarcane productivity [22]. Despite the extensive cultivation system in fertile, deforested areas, the need for technological

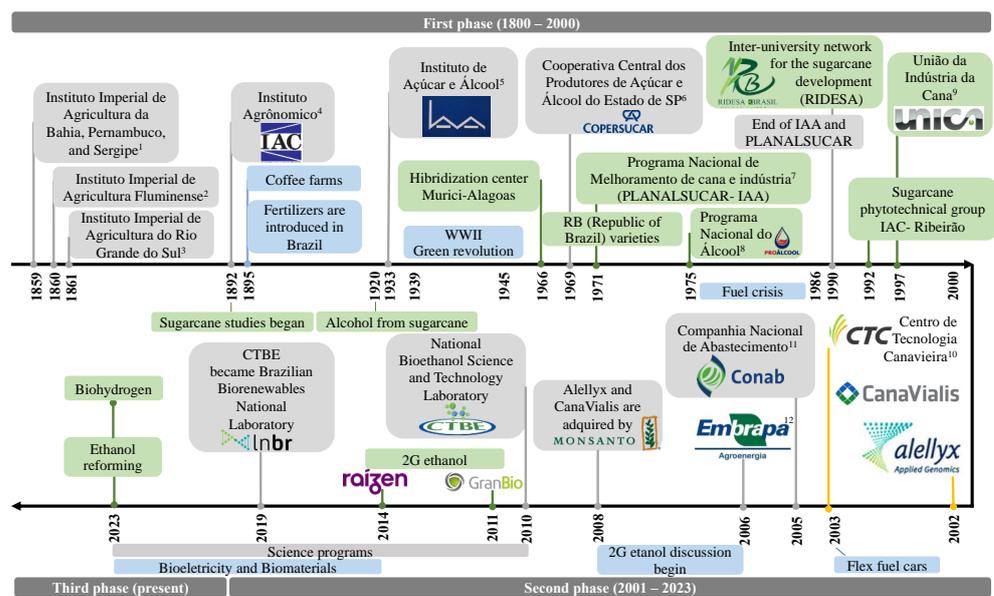
incentives and information on Brazilian soil management were the main limitations of sugar's market demand back then [23]. Sugar was Brazil's first and only commodity produced for over 300 years [22].

Brazil's sugarcane production and planted area significantly increased from 1900 to 1980 (Figure 1a). At the beginning of the 20th century, central mills still produced sugar for subsistence and/or exportation [24]. Frequent export drops, along with external market competition (beet sugar) and World War II, demanded sugarcane industrialization and the internal maintenance of the Brazilian economy. The sugar industry has adapted to produce anhydrous alcohol, aiming for its addition to gasoline. After the 1950s, the sugarcane-planted area and production increased almost linearly, reaching an area approximately five times greater than that at the beginning of the century (Figure 1a).



**Figure 1.** Evolution of sugarcane production in Brazil. Historical production and planted area of sugarcane during the 20th century (a) and between 1980 and 2021 (b). M: million, and ha: hectare. Data obtained from IPEA (<http://www.ipeadata.gov.br/>) and Conab (<https://www.conab.gov.br/>) accessed on 23 May 2023.

The regulation, commercialization, technology, and databasing of sugarcane, sugar, and alcohol production were achieved with the leadership of governmental institutions. Studies on sugarcane began in 1892 with Franz W. Dafert, who tested 42 varieties of *Saccharum officinarum* under two cultivation conditions at the Agronomic Institute of Campinas (IAC, Brazilian acronym) [25]. Gummosis and the mosaic virus spread throughout the sugarcane fields, reducing production and alerting people about the necessity of breeding and developing more appropriate cultivating systems (Figure 2).



**Figure 2.** Brazilian timeline of scientific, technological, and industrial sugarcane research and development programs from 1859 to 2023, focusing on improving sugarcane's agronomical traits. Large

historical events happening worldwide are in blue boxes. Grey boxes are the institutes created to study crops in Brazil. Green boxes are specific research institutes that have sugarcane as their main target. Yellow refers to private companies that developed sugarcane varieties. <sup>1</sup> Imperial Institute of Agriculture of Bahia, Pernambuco, and Sergipe. <sup>2</sup> Imperial Institute of Agriculture Fluminense. <sup>3</sup> Imperial Institute of Agriculture of Rio Grande do Sul. <sup>4</sup> Agronomical Institute. <sup>5</sup> Alcohol and Sugar Institute. <sup>6</sup> Central Cooperative of Sugar and Alcohol Producers of the State of São Paulo. <sup>7</sup> National Sugarcane and Industry Improvement Program. <sup>8</sup> Alcohol National Program. <sup>9</sup> Sugarcane Industry Union. <sup>10</sup> Sugarcane Technology Center. <sup>11</sup> National Supply Company. <sup>12</sup> Brazilian Agricultural Research Company.

#### 4. The First Phase of Brazilian Investments in Science and Technology in the Sugarcane Sector: An Analysis from 1969 to 2000

Although government investments in sugarcane have been obvious since the 1500s, science and technology displayed a transition phase from the 1930s onwards, with science (mainly breeding) being developed by government-funded institutions. We artificially set the beginning of the first phase of investment in science, technology, and financing of the sugarcane sector in 1969, because this is the year in which we detected the first record of a scientific publication in the scientific databank we used in this review.

Investment in the production of ethanol from sugarcane in Brazil can be dated back to 1933, when the Institute of Alcohol and Sugar (*Instituto de Álcool e Açúcar*—IAA) was founded with the intervention of the Brazilian state to regulate sugarcane activity; this lasted until the mid-1980s [26]. IAA was responsible for establishing sugarcane production quotas for mills and suppliers, managing the price of raw materials and products (sugar and alcohol) and the export rules. In 1966, this institute and the productive sector of Alagoas created a hybridization station in *Serra do Ouro* (Murici, Alagoas), where the first Brazilian sugarcane varieties, called RB (referring to *República do Brasil*), were developed [27]. At first, genetic breeding prioritized the genotypes introduced from other countries, such as India, Java, and the USA [25]. In 1971, IAA started the National Sugarcane Breeding Program (*Programa Nacional de Melhoramento da Cana de Açúcar*—PLANALSUCAR), fundamental for the implementation of the National Alcohol Program (*Programa Nacional do Álcool*—PROÁLCOOL) in 1975 (Figure 2).

The PRO-ÁLCOOL Program boosted the sugar and alcohol industry and supported ethanol fuel (hydrated) as a principal energy matrix in the country (Figure 1) to compete with oil fuel. The Brazilian dependence on oil as a primary energy source grew from 13.2% in 1940 to 41.7% in 1977 [28]. This program increased sugarcane production, expanding the planted areas with qualified technical support to generate more efficient hybrids with a high sugar content and disease resistance [28]. Moreover, thanks to PRO-ÁLCOOL, new yeast strains were selected, the fermentation processes were optimized (continuous, semi-continuous, and discontinuous), and other biomasses were studied (e.g., cassava, babassu, and sorghum), which contributed to the increased productivity of fermentation [28]. The effectiveness of PRO-ÁLCOOL allowed the sale of cars powered exclusively by alcohol in 1978. As a result of the second oil crisis (1979), the Brazilian government decided to invest in ethanol as a fuel. However, the Brazilian strategy did not count on reducing oil prices, and ethanol production did not meet the internal demand. At the same time, an increased demand in the market for sugar shifted industrial production, decreasing ethanol production even more [13].

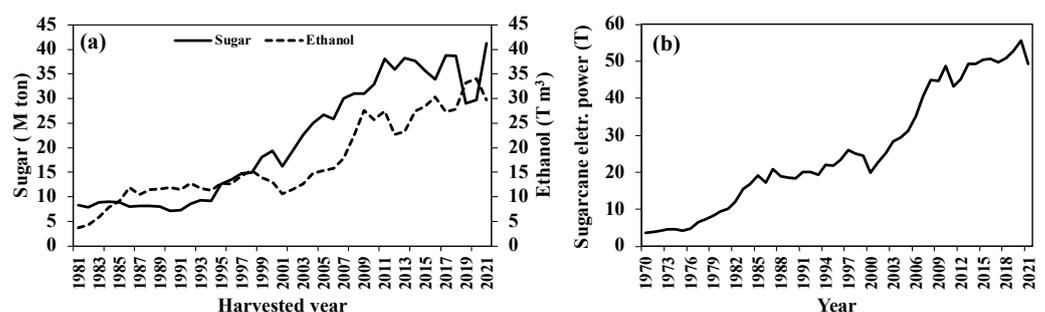
In 1990, the government closed the IAA/PLANALSUCAR. Its entire physical structure, human resources, and technologies were transferred to Federal Universities: The Federal Universities of Alagoas, Mato Grosso, Paraná, Piauí, Sergipe, São Carlos (in São Paulo State), Viçosa (in Minas Gerais State), Goiânia (in Goiás State), and the Federal Rural Universities of Pernambuco and Rio de Janeiro [27]. This change created the Interuniversity Network for the Development of the Sugarcane Industry (RIDESA for the Brazilian acronym) (Figure 2), which decentralized the sugar and ethanol sector. In São Paulo State, the Phytotechnical

Group of Sugarcane was created in 1992 in Ribeirão Preto, and the Sugar Cane Program was launched by the Agronomic Institute of Campinas (IAC) in 1994, integrating research in genetics, physiology, phytopathology, entomology, pedology, fertility, and climatology. To date, the IAC's sugarcane program has generated and disseminated knowledge on sugarcane to researchers, companies, industry, and farmers [25].

The Cooperative of Sugar and Alcohol Producers of the state of São Paulo (*Cooperativa Central dos Produtores de Açúcar e Álcool do Estado de São Paulo Central*—COPERSUCAR) was created in 1969 together with its research center in Piracicaba, in the state of São Paulo. COPERSUCAR had an Experimental Station in Camamu, in the state of Bahia, which developed hybrid sugarcane varieties (named SP varieties) suitable for the climatic conditions of this region (Figure 2). In the 1970s, the IAC signed an agreement with COPERSUCAR, which enabled the introduction of 678 genotypes from several countries in Camamu [25]. COPERSUCAR became extinct in 2003, and all the genetic resources generated were acquired by its substitute, the Sugarcane Technology Center (*Centro de Tecnologia Canavieira*—CTC), which became the leading Brazilian sugarcane breeding company with its then-named CTC varieties [27].

All these programs were essential for the generation of new technologies and varieties, as well as sugarcane development and data collection, which improved the production sector (Figure 1). Since 1980, the database Sugarcane Industry Union (*União da Indústria da Cana de Açúcar*—UNICA) started to gather data on sugarcane production and the total sugarcane planted area (Figure 1a). In 2005, a federal institution named *Companhia Nacional de Abastecimento*—(CONAB) was founded and started monitoring agricultural development in Brazil (Figure 2). The average sugarcane production increased from 50 to 90 tons per hectare with breeding programs and investment in science and technology for crop productivity [28].

From 1980 to 1998, juice extraction increased by 6% (from 90 to 96%) and fermentation yield by 7% (from 84% to 91%) [16], while the planted area and sugarcane production doubled (Figure 1b). Ethanol production increased from 664,000 m<sup>3</sup> (1977 harvest year) to 3.7 million m<sup>3</sup> (1981 harvest year). The financing of new distilleries also contributed to the growth of the sugar and alcohol industry, reaching 11.5 million m<sup>3</sup> in 1985 (Figure 3a). In that same period, in which production was breaking records, the increase in oil prices (second oil crisis—1979) led to a new market for vehicles powered only by alcohol [29]. The government has provided tax incentives, controlled alcohol prices, and directed companies to create the necessary systems for storing, transporting, and distributing hydrous alcohol to cars. Together, these actions led to a rapid expansion of alcohol-powered vehicles, representing 90% of fleet renewal in the 1980s [30]. However, the crisis caused by the shortage of alcohol and the closure of the IAA (in 1990) marked the end of the government incentive program (Figure 2), reflected in the ratio between sugar and ethanol production from 1994 to 2000 (Figure 3a). Sugar production increased five times while ethanol production was maintained at 12 million m<sup>3</sup> annually. Ethanol production declined and started to recover only from 2008 onwards. Even so, sugar accounted for most of production until the 2019 harvest, which saw balanced production levels between the two main sugarcane products.



**Figure 3.** Ethanol and sugar production and ethanol electrification. (a) Sugar and ethanol production in Brazil between 1980 and 2021. M: million, T: thousand, ha: hectare. (b) Production of renewable primary

energy in one ton of oil equivalent = T (1 T represents 41.868 gigajoules). Data obtained from IPEA (<http://www.ipeadata.gov.br/>) and Conab (<https://www.conab.gov.br/>) accessed on 23 May 2023.

## 5. The Second Phase of Brazilian Investments in Science and Technology in the Sugarcane Sector: An Analysis from 2001 to 2023

The PRO-ÁLCOOL and the creation of several research institutes have boosted sugar and ethanol production, although basic knowledge about sugarcane biology and development hampered biotechnological manipulation for more productive and stress-resistant varieties [31–34].

At the end of the 1990s, the São Paulo Research Foundation (*Fundação de Amparo à Pesquisa do Estado de São Paulo*—FAPESP) joined efforts with CTC to develop sugarcane research [35], especially in genomics. The SUCEST (SUGarCane Expressed Sequence Tags) program identified genes associated with agronomic traits, such as sugar yield, cell wall, and resistance to biotic and abiotic stresses (Figure 2) [36,37]. This program and several others marked the beginning of studies on sugarcane molecular biology and bioinformatics (Figure 2). They allowed the foundation of the plant genomics companies Alellyx Applied Genomics (2002) and CanaVialis (2003) [38]. Although Alellyx has developed technology with several crops (citrus, eucalyptus, grapes, and soybeans), most of the budget was directed towards developing transgenic sugarcane [39]. As an alternative to genetic transformation, CanaVialis has improved sugarcane varieties using classic breeding and provided consultancy services to farmers. In 2008, both companies were bought by Monsanto (Figure 2). BASF, Syngenta, and DuPont established their respective research centers to develop new sugarcane varieties and crop technologies [34], leading to pre-sprouted seedlings, sugarcane “seed,” and precision agriculture after one decade.

In 2003, the flex-fuel technology that uses an electronic injection controlled by sensors to detect ethanol and gasoline permitted the choice between those fuels to run vehicles [40]. After the launch of flex-fuel vehicles in Brazil, the sale levels of ethanol fuel cars increased by 90% [31] which, consequently, increased ethanol production from 10 billion m<sup>3</sup> in 2001 to over 30 billion m<sup>3</sup> in 2019 (Figure 3a).

To achieve the global demand for ethanol with the growing number of cars and the need for renewable fuels, second-generation technologies (2G) have emerged. This 2G ethanol converts agroindustrial lignocellulosic residues into fermentable sugars by cell wall hydrolysis, followed by yeast fermentation and distillation. In Brazil, 2G ethanol is produced from sugarcane bagasse and straw [33,41,42]. This second green energy revolution became necessary in Brazil in 2006. Once again, researchers needed the scientific and technical knowledge to support a new industrial demand [42]. Catalytic attacks by the cell wall’s mechanical, physical, chemical, or biological forces are considered difficult despite the recalcitrance of the polysaccharides assembled with lignin [43]. Lignin is a phenolic compound that needs to be removed from the biomass to produce ethanol 2G that can be submitted for green chemistry and biorefinery to generate value-added products such as vanillin [44]. Research and development on 2G ethanol has focused on sequencing the sugarcane genome, developing sugarcane genetic transformation protocols, characterizing the architecture of the sugarcane cell wall, discovering and understanding the action of enzymes on polysaccharides, and developing biomass pretreatments and processes to ferment pentoses (five-carbon sugars).

To face these major challenges, the FAPESP Bioenergy Research Program (BIOEN), the National Institute of Science and Technology of Bioethanol (INCT of Bioethanol), the Brazilian Bioethanol Science and Technology Laboratory (CTBE), and the Center for Biological and Industrial Processes for Biofuels (CeProBio) were created. Among the Brazilian research funding agencies, the following stood out: The Financier of Studies and Projects (FINEP) and the National Council for Scientific and Technological Development

(CNPq), both linked to the Ministry of Science, Technology and Information, and FAPESP, linked to the São Paulo State Government [27].

To ensure the presence of renewable sources in the national energy balance, new programs and institutes were created, such as the *Embrapa AgroEnergia*, the National Program for the Production and Use of Biodiesel (*Programa Nacional de Produção e Uso de Biodiesel*—PNPB), the National Agroenergy Plan (*Programa Nacional de Agroenergia*—PNA), and the National Bioethanol Science and Technology Laboratory (*Laboratório Nacional de Ciência e Tecnologia do Bioetanol*—CTBE), to use biomass from different crops fully in the energy production chain [45]. CTBE was created by the Center for Management and Strategic Studies (CGEE) for exploratory research by the Interdisciplinary Center for Energy Planning (NIPE/UNICAMP) to identify the limiting factors of ethanol production. CTBE aimed to assess the impact of new agricultural and industrial technologies on ethanol production and the environmental, societal, economical, and logistical shifts in the sector (Figure 2). Later, CTBE was renamed the Brazilian Biorenewables National Laboratory (LNBR), and added to the other technology centers of the National Center for Research in Energy and Materials (CNPEM) complex [46].

The company Granbio was founded in 2011 to develop sugarcane varieties with low production cost, high biomass, and energy efficiency that can be cultivated in restricted areas to avoid competition between biofuel feedstock and food production [47,48]. Those sugarcane varieties were called energy cane, of which 11 were registered in Brazil under the name of Vertex. Raízen, another company formed by the joint venture between Shell and Cosan, operates most of Brazil's sugar, ethanol, and energy-producing systems. Raízen also operates a 2G ethanol industrial manufacturing process; others are under construction. In addition, sugarcane straw and bagasse can be burned for bioelectricity co-generation (Figure 3b).

As a result of these incentives and investments in research, activities for industrial biotechnology and green chemistry were expanded in Brazil [45]. Ongoing studies focus on breeding sugarcane to improve the control of pests in agriculture and to face the challenges of global warming. In 2021, the Brazilian Ministry of Agriculture, Livestock, and Supply [49] registered 214 new sugarcane varieties (68 RB, 38 CTC, 37 SP, 33 IAC, and 38 other varieties).

The energy balance of the Brazilian ethanol production chain has changed. Before PROÁLCOOL, the energy balance was negative, but fossil fuels were replaced in the sugarcane mills, and the energy surplus from bagasse was sold to the energy grid [50]. As a result, Brazilian bioethanol has lower production costs, making it competitive with other fuels, and has the advantage of reducing ~ 80% of GHG emissions [51]. A new phase is currently being implemented with a partnership between Shell and the University of São Paulo involving the Research Center of Green House Gas Innovation (RCGI) and the INCT do Bioethanol. For the first time in the world, an ethanol reforming unit for the production of green hydrogen is underway [52].

## 6. The Production of Scientific Knowledge in the Sugar-Energy Sector: A Bibliometrics Analysis of Phases 1 and 2

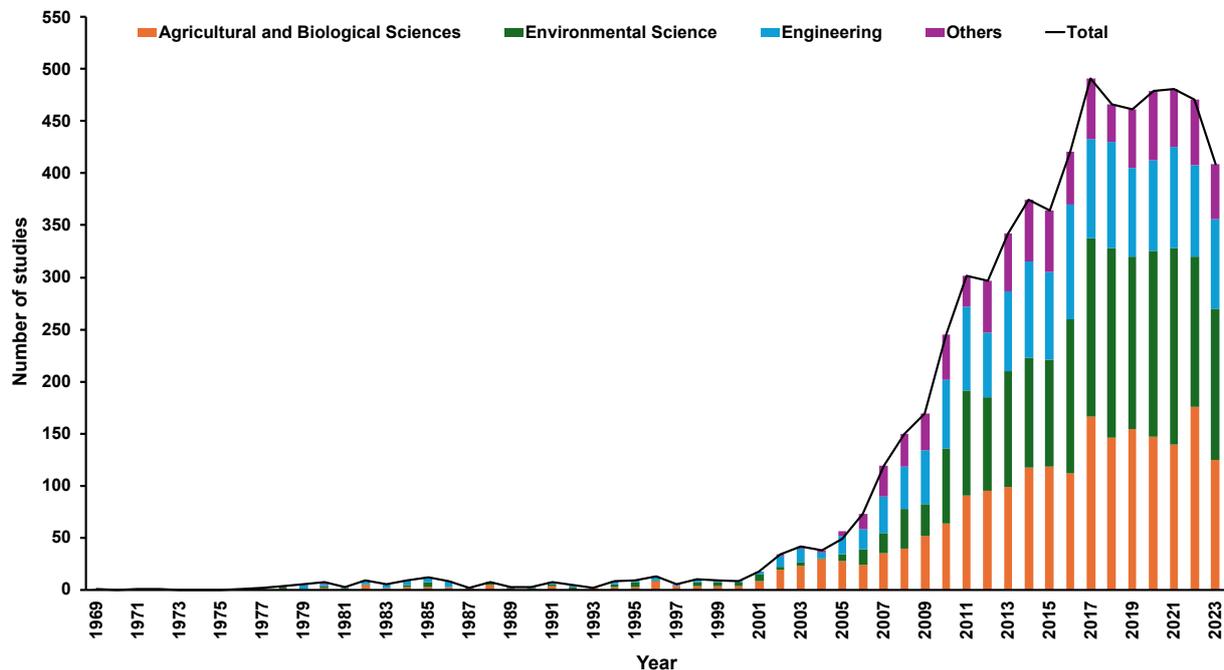
The quality and number of articles and documents published on bioenergy were evaluated through a bibliometric search in the Scopus/Elsevier database to evaluate scientific research production. Bibliometrics is a statistical methodology used to evaluate and quantify the number and tendency of growth of a specific subject (in our case, bioenergy and sugarcane research) in the literature [53].

The bibliometrics of sugarcane and ethanol science revealed the number of journal publications by country and the thematic categories for the research areas. These analyses were performed in December 2023, using the following keywords: sugarcane AND (ethanol OR bioethanol OR bioenergy OR alcohol). The search was performed for documents published between 1900 and 2023. We recovered 6456 articles from 111 countries (Supplementary Table S1), with the first publication from 1969, entitled “Products of arginine catabolism in

growing cells of sugarcane” [54]. The number of publications remained constant between 1969 and 2000 and increased exponentially from 2005 onwards. The most productive year was 2017, with 491 articles (Figure 4). After analyzing those articles by specific areas, such as agriculture and biology, environmental sciences accounted for 65% of the publications (2077 and 2066 articles, respectively) (Figure 4), whereas engineering accounted for 22% (1457 papers) and others for 13% (864 papers) (Figure 4). These data represent the engagement of basic sciences in improving sugarcane productivity, which is more institutionalized in research institutes, while research on the industrial part has often not been published, with all the knowledge belonging to the companies that developed research to improve ethanol production and automobile industries.

The first historical phase, with PRO-ÁLCOOL and several research groups being created, saw an increase in published works after 1975 (Figure 4). Before this time, most research was carried out directly by industry and private sectors, which reduced the ability to estimate knowledge produced during this period. The lower speed of pre-2000 publication processing may be related to the lower number of publications that came before and the increase afterward. The new technologies, equipment, and computer systems accelerated the publishing process, which led to a vertiginous increase in the rate of knowledge spread through scientific journals [55].

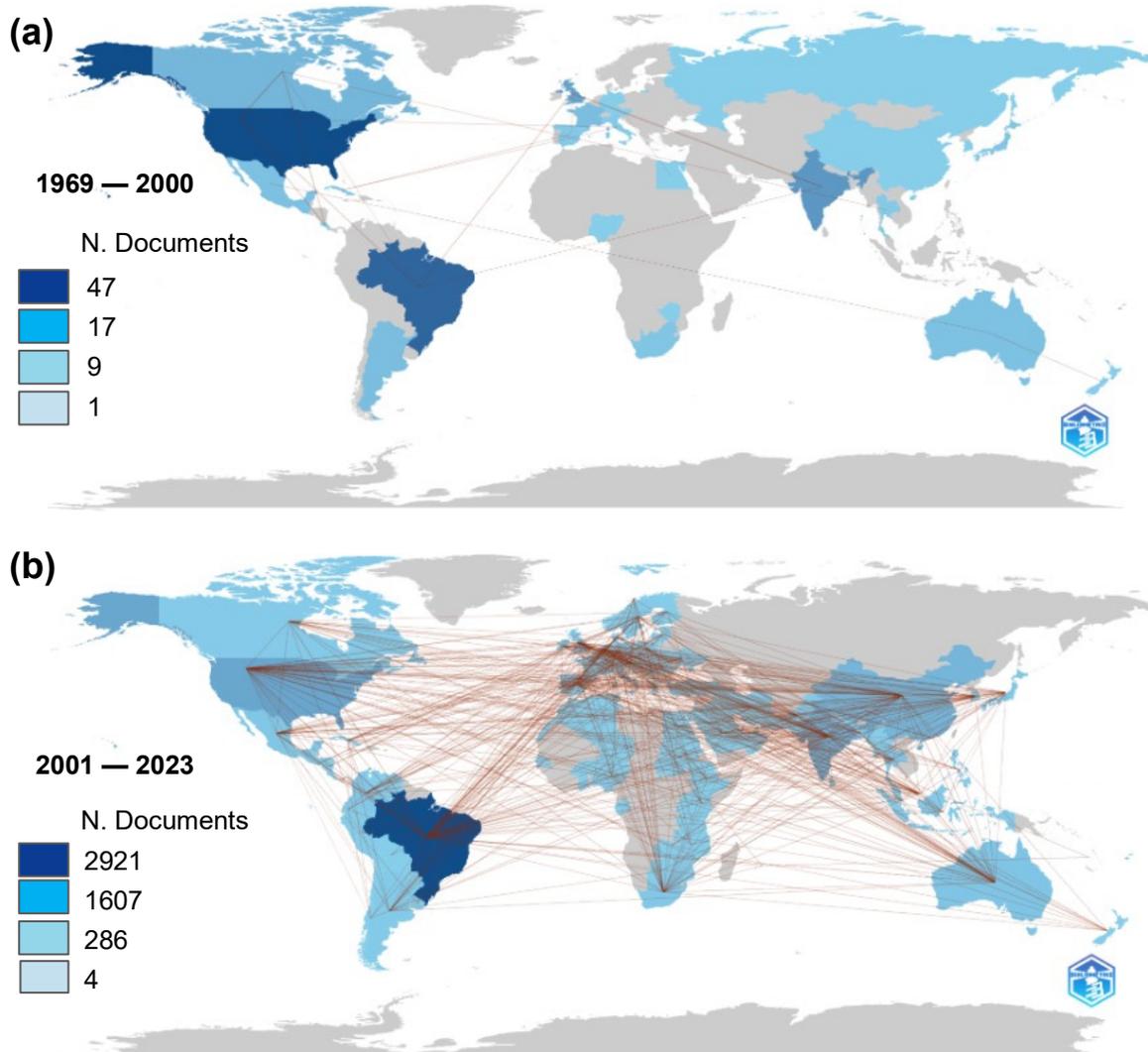
Citation numbers are another parameter that can indicate research visibility and preference by the research community in a given period. The most cited article was “Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products,” with 3751 citations [56]. In Brazil, “Ethanol for a Sustainable Energy Future” [5], addressing ethanol from Brazilian sugarcane as an energy commodity fully competitive with gasoline, received a high number of citations (1088).



**Figure 4.** Scientific production by category from 1969 to 2023. Data are represented by the frequency of studies per year in the categories of agriculture, environmental science, engineering, and biology. The search was carried out in the Scopus database up to 31 December 2023.

The increase in the number of publications in the last two decades appears to be related to the connections among research groups (Figure 5). These data can be parameterized with bibliometric analysis, which shows the number of authors, publication types, collaborators, and scientific contributions to bioenergy and sugarcane ethanol advancement. In the first phase of sugarcane science and technology development (1969–2000), the countries

that contributed most to the dissemination of scientific knowledge were the USA, Brazil, India, the UK, Argentina, Canada, France, Mexico, South Africa, and Australia (Table 1 and Figure 5). As mentioned above, the second phase (2001–2023) increased research productivity, the internationalization of Brazilian research, and collaborations (Table 1 and Figure 5). During this time, Brazil led the number publications, followed by the USA, India, China, Australia, Thailand, the UK, Japan, Mexico, and The Netherlands (Table 1).



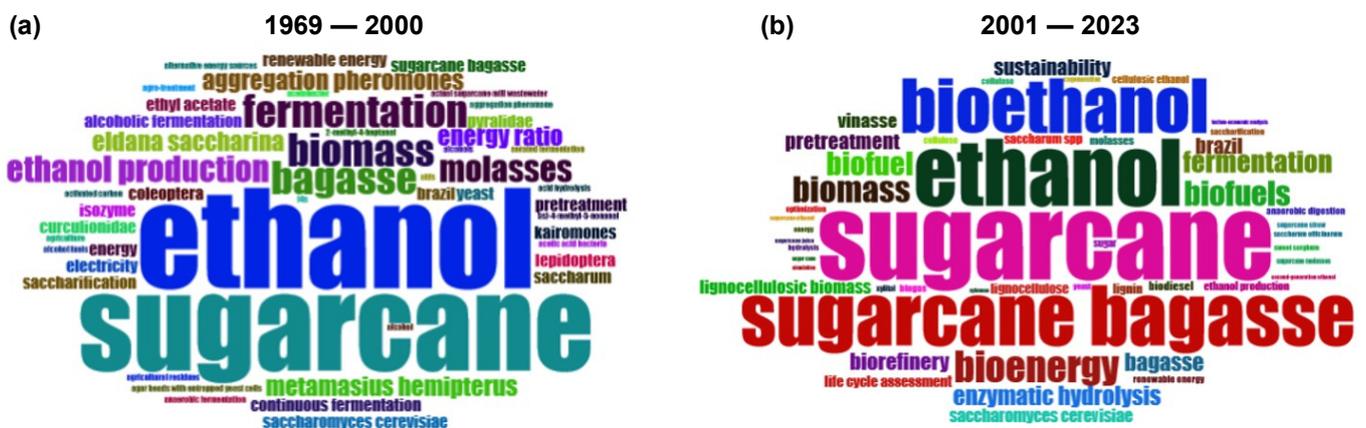
**Figure 5.** Worldwide network of publications related to bioenergy, bioethanol, ethanol, or alcohol in sugarcane. World maps from (a) the first wave (1969–2000) and (b) the second wave (2001–2023). Blue color intensity represents publication number, and red lines represent the collaboration between countries. The search was carried out in the Scopus database up to 31 December 2023.

Co-word analysis is an effective tool for analyzing hot topics and search trends by title, keywords, and abstract from published work, and is therefore important for content analysis [53]. Using the “bibliometrix” package from R-4.0.0 [57], a network with the 50 most frequent keywords was constructed to explore the data recovered. The terms studied over the two phases showed that changes in scientific research could be analyzed by word frequency in keywords (Figure 6). Sugarcane, ethanol, bagasse, and molasses were the most frequently used keywords from 1969 to 2000. However, fermentation processes, yeast names, and crop pests were highlighted (Figure 6a), suggesting the focus on 1G bioethanol (sucrose fermentation). These keywords shifted from 2001 to 2023, when sugarcane bagasse,

bioethanol, bioenergy, and biofuel were highlighted along with biomass pretreatment processes (lignocellulose biomass, pretreatment, biorefinery, and enzymatic hydrolysis) (Figure 6b), focusing on 2G ethanol. The ‘bio’ prefix added to the most frequently used terms indicates that research on sugarcane ethanol has been associated with the evolution of socio-environmental ethics, incorporating the ideas of sustainability from the latter decade [58].

**Table 1.** Scientific production by country regarding bioenergy, bioethanol, ethanol, or alcohol in sugarcane. Single publications (SCP). Multiple publications (MCP). The search was carried out in the Scopus database up to 23 March 2023.

Time 1969–2000				Time 2001–2023			
Country	Articles	SCP	MCP	Country	Articles	SCP	MCP
United States	21	19	2	Brazil	2237	1473	387
Brazil	19	17	2	United States	597	284	121
India	11	9	2	India	429	311	142
United Kingdom	9	5	4	China	373	261	69
Argentina	5	5	0	Thailand	147	101	28
Canada	5	3	2	Australia	130	47	35
France	4	2	2	United Kingdom	125	34	32
Mexico	4	3	1	Mexico	106	59	20
South Africa	3	3	0	Japan	105	34	24
Australia	2	1	1	Netherlands	102	30	29



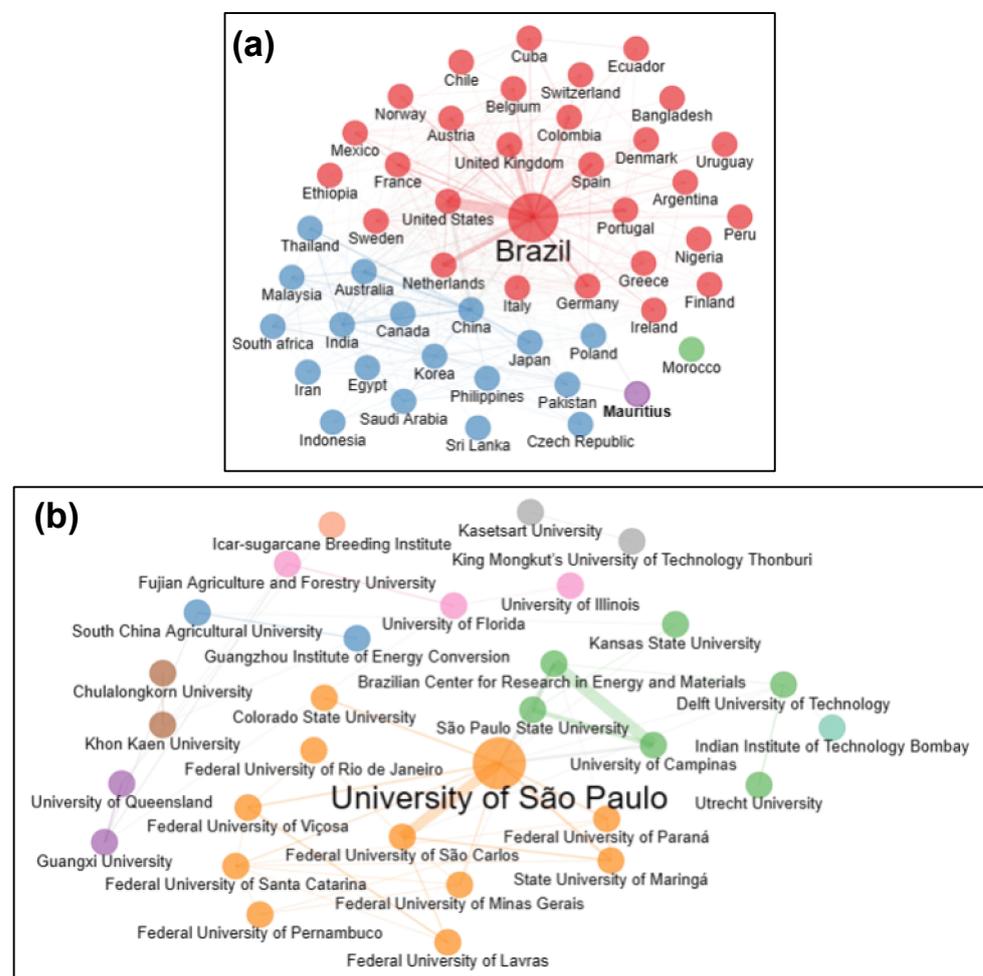
**Figure 6.** Keyword maps of sugarcane and ethanol published works. (a) First wave (1969–2000) word map. (b) Second wave (2001–2023) word map. The larger the word size, the higher the frequency of the word in studies. The search was carried out in the Scopus database up to 31 December 2023.

Brazil has become the largest sugarcane producer due to advances in policies that invest in the science and technology of agriculture and refineries [59,60] (Figure 1). The country consolidates leadership in sugarcane and ethanol production, as seen in Figure 7. Network research in sugarcane bioethanol shows 49 countries that contributed to scientific advancement in this area (Figure 7a). Brazil has been collaborating mainly with the USA and European countries (Table 1 and Figures 5 and 7). Despite governmental investment in science and technology, which became a benchmark in sugarcane production [61], after the 2000s, China only appeared in fourth place in the list of countries with the most publications (Table 1).

The internationalization programs in Brazil, funded by CNPq and FAPESP, have stimulated collaboration with the USA, UK, The Netherlands, Colombia, Spain, Portugal, and Germany (Figure 7a). China and India had a collaboration network with Canada, Japan, Thailand, and Australia but lacked stronger collaborations with Brazil. The interactions between world institutes and universities highlight Brazil, and especially the University

of São Paulo (USP) (712 articles), University of Campinas (UNICAMP) (416), São Paulo State University—(UNESP) (296), Federal University of São Carlos (UFSCAR) (213), and the Brazilian Center for Research in Energy and Materials (149). The University of São Paulo had the highest number of articles and interactions with other central nodes, with the Federal University of São Carlos (part of RIDESA) in its subnet. The state of São Paulo had research funding advantages in developed agriculture because it accounts for 55% of the Brazilian sugarcane-cultivated areas and produces 48.5% of the country's ethanol [12,62].

It is important to highlight that the bibliometry brought about in this work refers exclusively to the science produced and does not contemplate political and economic aspects that would allow a more comprehensive evaluation of the sugarcane-ethanol-producing system in Brazil. Our study did not focus on the (agro)engineering of automobiles or the ethanol industry itself, as technological development inside the industry is normally protected by intellectual property. On the other hand, the science production capacity advances function as a reliable indicator of what may happen in industry and society in the future.



**Figure 7.** Collaboration network of scientific productions related to sugarcane and ethanol from 1969 to 2023. (a) Countries that published articles with the theme bioethanol and/or sugarcane. (b) World research groups on sugarcane bioenergy. The search was carried out in the Scopus database up to December 2023. Each node represents a country, and its size indicates the contribution to research and the number of collaborations with other groups. The thickness of the lines reflects the rigidity of cooperation between countries. Brazil has the highest degree of centrality and is the hub of research on sugarcane bioenergy. The groups were formed based on the Louvain method [63], and each color represented the groups that collaborated more with the published works. Parameters: minimum cluster of 1, terms greater than or equal to 10, association strength method.

## 7. The Future of Brazilian Ethanol and Climate Change

As the global temperature is likely to increase above 1.5 °C in the following decades, CO<sub>2</sub> emissions must reach net zero and the reduction of greenhouse gas emissions must be more effective [62,63]. To achieve these goals, the Intergovernmental Panel on Climate Change (IPCC) reported that governments must comply with the Paris Agreement [64,65], and the world has been discussing how to capture, use, and store carbon. Bioenergy with Carbon Capture and Storage (BECCS) is a technology that may help achieve negative carbon emissions via plant photosynthesis [66]. The biomass accumulated is converted into liquid or solid fuel that will be burned, and the CO<sub>2</sub> produced in the industrial process can be captured and stored underground. Thus, sugarcane and the advantages of ethanol reappear as sustainable promises. The capture of the carbon released by the ethanol production chain could benefit from BECCS to reach negative carbon emissions. Programs such as *RenovaBio* in Brazil have directed industries and agribusiness towards negative emissions and the circular economy of ethanol. These new sustainability-related approaches characterize a third phase of ethanol science and technology that involves many sectors of industry modernization, such as transport and distribution logistics, and a deeper modification of ethanol as a raw material for hydrogen production.

Other ethanol production systems rely on sugar beet (Europe) or corn (the USA), but the Brazilian sugarcane system is the most efficient. The production of 1L of corn ethanol requires nine times more energy than the production of 1L of sugarcane ethanol [67]. As mentioned above, Brazil has a successful history in the science, technology, and development of sugarcane (Figure 2) and its derivative products' logistics, manufacture, and commercialization (sugar, bioethanol, and bioelectricity). This was possible with the engagement of the public and private sectors, along with universities and research institutes.

Generating bioethanol from vinasse residues is a promising practice that could reduce the environmental impact of ethanol production. Vinasse is a by-product of alcohol production that contains high concentrations of organic matter, nutrients, and pollutant potential. This by-product can be anaerobically digested to produce biogas (a mixture of methane, carbon dioxide, and hydrogen sulfide), used for electrical and thermal energy or as a fuel. The residue of biogas production could be used as a fermentation substrate for ethanol production [68]. This approach aggregates value to residues and reduces the emission of greenhouse gases and the consumption of raw materials [69]. The circular economy in industrial processes contributes to climate change mitigation and sustainable development, with social benefits.

Sugarcane is at the forefront, with a promising market that can be expanded worldwide. Investing in 2G ethanol and higher sugarcane productivity are paths followed by Brazil to increase world energy production to supply domestic and international markets. To make 2G ethanol profitable, research and development are still needed. Most sugarcane straw is still left in the field, and much of the bagasse is burned for bioelectricity. Using these biomasses to generate additional ethanol is more efficient in energy but still expensive.

Brazil's third bioethanol phase began with ethanol steam reforming to generate green hydrogen sustainably [70]. Hydrogen became strategic for governments and companies after the post-pandemic policies, despite its low or zero-carbon energy source [71]. However, the country has been developing a hydrogen R&DI strategy for the past 20 years, with ethanol, hydro, wind, and solar technological routes to potentially supply domestic and international markets [72]. In 2002, the Brazilian Program for Hydrogen and Fuel Cell Systems (PROCaC) was launched by the Ministry of Science and Technology (MCT), and in 2005, the program was renamed the Program of Science, Technology, and Innovation for the Hydrogen Economy (PROH2). In the same year, the Ministry of Science and Technology produced a roadmap for structuring the hydrogen economy in Brazil. From 2005 to 2015, with the participation of the MME (*Ministério de Minas e Energia*), EMTU/SP (*Empresa Municipal de Transporte Urbano de São Paulo*), ABC/MRE (*Agência Brasileira de Cooperação* and the *Ministério de Relações Exteriores*), GEF (Global Environmental Fund), FINEP (*Financiadora de Estudos e Projetos*), and UNDP (United Nations Development Program), a fleet of hydrogen

fuel cell buses was developed, and three prototypes circulated in a metropolitan corridor of the city of São Paulo [72]. In 2018, the Brazilian government released a Plan for Renewable Energies and Biofuels 2018–2022 to encourage and develop storage technologies, fuel cells, flywheels, and the use of renewable energies and fuels for hydrogen production [72]. In 2021, innovation in the hydrogen energy vector was expanded, and the legal framework and regulations were consolidated to improve the market [72].

Most of the infrastructure for ethanol reforming is already available in Brazil, and little investment is needed to overhaul the infrastructure for production [72]. The endothermic process can generate hydrogen with oxidants like oxygen, water, and carbon dioxide [73]. The CO<sub>2</sub> emissions during hydrogen production by ethanol are lower than their absorption during sugarcane cultivation, assuming a negative carbon emission [74]. In addition, the hydrogen production from bioethanol can be coupled with proton membrane fuel cells for the co-generation of heat and power [75]. Nowadays, renewable hydrogen production in Brazil is public or publicly financed R&DI, and is still in the prototype stage [72]. Electric and hybrid cars, buses, and trucks are prospective directions for the near future for energy derived from BECCS, fueling transportation with negative carbon emissions.

Another possibility for sugarcane ethanol use is for sustainable aviation fuel (SAF) production [76]. The aviation sector is responsible for 2.5% of GHG emissions. Thus, new strategies and resources are needed to improve CO<sub>2</sub> efficiency and reduce carbon emissions. SAF can be produced from the hydrotreating of oil-based feedstocks (HEFA), the dehydration and oligomerization of ethanol (alcohol-to-jet, ATJ), the direct conversion of sugar to hydrocarbon (DCSH), the Fischer–Tropsch (FT) process of renewable or fossil feedstock, FT coupled with the alkylation of light aromatics, the hydrothermolysis of oil-based feedstocks (CH), and the hydrotreating of bio-derived hydrocarbons [77,78]. The possibility of using biomass or even sugars and ethanol 1G and 2G for SAF production opens a new branch for Brazil's circular economy of sugarcane. An interesting possibility regarding biotechnology would be the production of lipids (alternatively to sugars) named "oilcane" in sugarcane, so that the plant could be used for SAF, for instance [79].

The establishment and development of sugarcane and governmental policies have made Brazil an example in bioenergy production. The creation of several science institutes, the dissemination of the knowledge acquired, the development of adapted varieties, the optimization of the process, and the fermentation of complex sugars have made the country one of the world's main ethanol producers. The continuous development of ethanol production, helping mitigate emissions, has led to new technologies and fuel developments such as green hydrogen and SAF to fulfill the production cycle and complete the circular economy.

Scientific research has contributed mainly to addressing bottlenecks in developing technologies, ranging from sugarcane productivity to the genetic improvement of cane varieties. Parallel with this are the industry sectors (manufacturing and vehicles), product distribution, and marketing, which are essential to bring the product to the consumer.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16104167/s1>; Table S1. Countries involved in the scientific production of sugarcane and the number of retrieved documents.

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