Feasibility of macaúba for biofuel production

EXECUTIVE SUMMARY

2022

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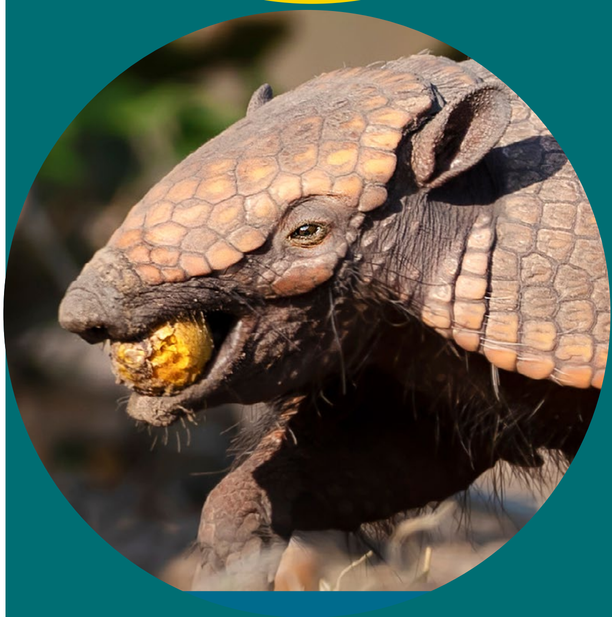


SUMMARY

01.

INTRODUCTION

Macaúba is a palm tree that reaches up to 25 meters in height, being a native species found in almost the entire country. Its fruit can be transformed into vegetable oil, animal feed or a dense biomass granulate with various industrial applications. Its productivity is high, reaching up to 6,000 liters per hectare, including oils extracted from its pulp and almond.

All parts of the macaúba fruit provide products with economic value. The most valuable component is the oil extracted from the pulp and almond. This process generates a co-product, the extraction residual pie, rich in fiber and of high nutritional value.

Suggested for food products or biodiesel, pulp oil contains 80% of fatty acids, with oleic acid predominating (65% to 70% of total fatty acids).

As for the almond oil, also used for food products, cosmetics and drugs, it contains approximately 70% of fatty acids (40% of lauric acid, 30% of oleic acid). In turn, the pulp and almond pies are used as animal feed, especially because 37% of the almond pie content is composed of proteins. Both pies are also used as fertilizers.

The endocarp (almond peel) contains high calorific value with potential for use as low ash, no sulfur and high density solid fuel.

Despite the diversity of possible uses of macaúba, the factor that accelerated both research and investments in its cultivation was the possibility of producing biodiesel and biokerosene to meet the goals established by Brazil and aviation companies in international commitments to face climate change.

By intensifying public policies to replace fossil fuels with biofuels, Brazil has moved towards meeting its climate goals, set out in the National Policy on Climate Change (PNMC) and its Nationally Determined Contribution (NDC) to the Paris Agreement. An example is the National Biofuels Policy (RenovaBio), which stimulates the decarbonisation of the fuel matrix, and the policy of gradually increasing biodiesel content in diesel blend to be burned in diesel cycle engines. These policies have contributed to the growth in demand for biodiesel in the country.

In addition to all its environmentally positive features, macaúba is attractive for its ability to meet the market demand sustainably and with quality. The species produces up to 6,000 liters of oil per hectare, although it is still in the initial stage of genetic improvement and management research. As for soybean, which accounts for 70% of the national biodiesel production, it yields only 500 liters per hectare.

MACAÚBA CAN PRODUCE UP TO
6 thousand
LITERS OF OIL PER HECTARE

This study presents the energy potential of macaúba and points out alternative planting strategies compatible with current market stage and species development. It also assesses the economic feasibility of macaúba cultivation in agroforestry systems with crop-livestock-forest integration, including degraded areas.

There are only two published scientific papers that present some results of the economic feasibility of macaúba. It is therefore necessary to continue its technological development so that it is possible to achieve minimally satisfactory economic results.

The results of a secondary data survey on such culture are also presented, along with the authors' analyses. In addition, information on the supply and demand of biodiesel was collected. In the light of such data and analyses, priority areas are suggested for planting as well as a minimum cash flow for the financial analysis of the species planting.

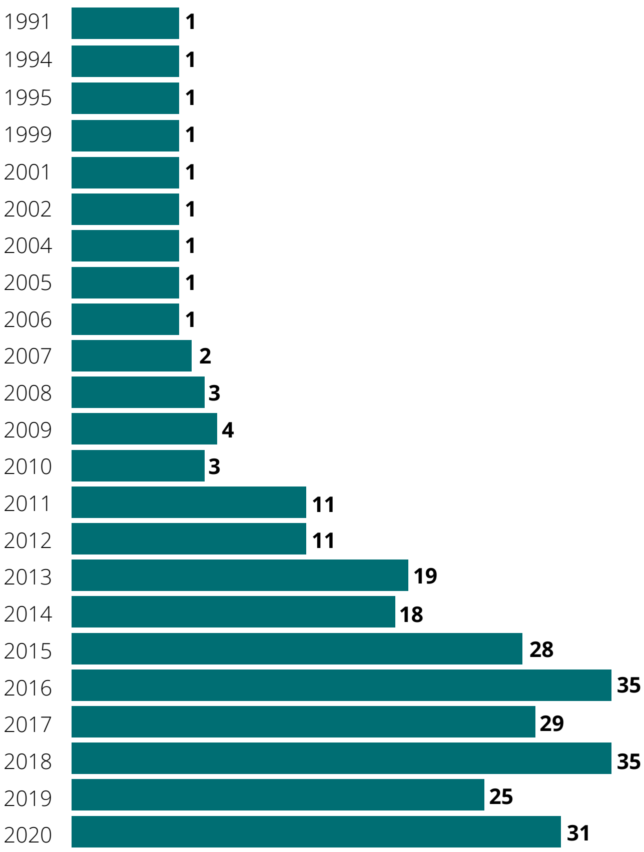
02.

MACAÚBA STUDIES STATE OF THE ART

Macaúba is the most researched palm among the 500 palm species in Brazil. 263 scientific articles were found on macaúba in the Web of Science, a platform that gathers databases also known as scientific citation indexes. The macaúba data collection time frame went from 1900 to 2020.

It was found that research on the subject is very recent – 90% of the articles were published over the last ten years, and half of that work took place in the last four years (2017 to 2020) given the interest in the species as alternative to fossil fuels. **(Graph 1)**

Graph 1. Articles published over the years



Several studies have been carried out in order to better understand the factors that influence the productivity of macaúba, such as temperature, altitude, solar incidence, precipitation, water deficit and the long seed dormancy, a challenging aspect to its agro-industrial processing.

The analysis of the articles marks the researchers' efforts to find solutions, point out perspectives and innovative uses for macaúba and other oilseed species. Many of the articles also investigate the bottlenecks of biofuel production industrial processes, and are concerned with testing various production procedures.

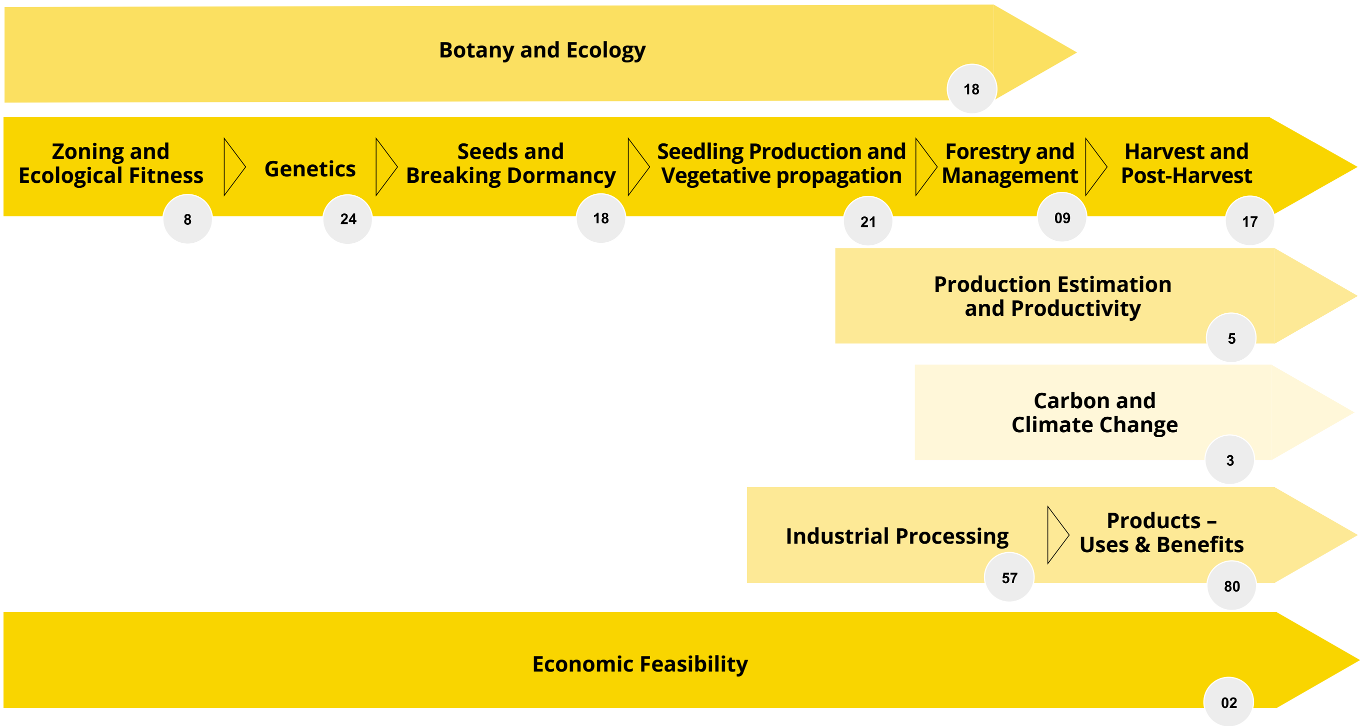
Articles were published on topics necessary for the species domestication, from zoning and edaphoclimatic fitness to the creation and adaptation of industrial processes of transformation. The research objects included the areas of the species botanical characterization, genetics, germination, seedling production, vegetative propagation, forestry, composition of fruits and possible applications, among others.

From reading the abstracts of the studies, this analysis classifies the articles in the research topics shown in **Chart 1**. In the items on ecology, botany and forestry, research generally focuses on management with the purpose of domesticating the species, as "the economic exploitation of macaúba is currently in transition, from extractivism to agricultural cultivation"[1].

Some themes require more research efforts, such as economic feasibility, quantification of carbon and impact on reducing greenhouse gas emissions. It is important to note that no studies were found yet of published cases, a fact that can be explained by the stage in which research is found.

[1] (PIMENTEL et al., 2015)

Chart 1. Articles published by research topics



Other articles focused on the effort to adapt the plant to the various types of soil and environment of the Cerrado. In the state of Goiás, for example, macaúba occurs when the soil has more than 50% of base saturation (eutrophic), with medium or high fertility, high potassium levels and precipitation between 1,300 and 1,700 millimeters per year, with an average temperature around 22ºC.

In the northern region of Minas Gerais, macaúba adapted to soils with higher natural fertility, where the semi-deciduous forest (loss of many leaves in dry season) was the primitive plant formation, showing that the species advances as pioneer, avoiding lack of nutrients and water extreme conditions.

Seeds and breaking dormancy

The breaking of seed dormancy has been an important challenge for the agro-industrial use of macaúba. As ecology and zoning studies of this palm point out, its long dormancy is related to the great adaptation of the species to Cerrado conditions, keeping the seeds alive, awaiting conditions conducive to germination.

A synthesized analysis identified 18 scientific articles on solutions to circumvent this important feature of the species. Part of these articles addresses the most appropriate conditions for in vitro germination of macaúba. Other studies preferred to focus on seedling production in nurseries.

When grown under low light intensity, the seedlings presented higher photochemical efficiency and minimized respiratory costs, with a positive carbon balance and lower irradiation.

Other researchers, on the other hand, test the influence of substrate fertilization in seedling development. Others study the time demanded by seedlings to remain in nurseries before they are ready for planting.

Forestry and management

Some studies aimed to guide the management of the species. One of them, for example, identified a peculiar macauba formation, the underground saxophone stems associated with tuberous roots. The research concluded that the saxophone stem represents an important adaptation of the species to environments impacted by human activities. The depth of the roots increases with age, and the distance they reach coincides with the crown projection, elements that influence the way in which fertilization and irrigation should be carried out.

Other researchers have studied the interaction of macaúba with hydrological processes, the species' responses to water deficit, the dynamics of carbon in intercropped pastures, and the relation with arthropods and mammals. Thus, it was possible to identify the seed predators that contribute to its dispersion.

One of the authors studied the interactions between livestock and the macaúba population, and another evaluated the resistance of embryos to fire, concluding that the fruit structure can facilitate seed resilience, even when subject to increasingly frequent fire events[2].

It is not surprising that the species is proving to be relevant in the recovery processes of degraded soils, due to its root system and the hydrological processes related to its cultivation. One of the articles quantifies the surface runoff of precipitation under various conditions[3]. In addition to confirming the best management practices, the authors found much higher values of water retention in the soil when compared to similar tests with other crops.

With regard to pests and diseases that threaten the macaúba crop, four studies were examined. Research efforts focus on the insects *Rhynchophorus palmarum* and *Cyclocephala forsteri*. A research describes the temporal variation of the presence of *Rhynchophorus palmarum*, vector of the nematode *Bursaphelenchus cocophilus*, beetle that causes red ring disease in palmtrees[4] and *Cyclocephala forsteri*, beetle that can significantly reduce the productivity of macaúba[5].

Researchers have also identified two different fungi on macaúba leaves in Puerto Rico[6][7].

Two articles stand out with regard to the behavior of macaúba under climate change conditions. The first shows that plants grown with CO_2 higher concentrations are more likely to recover from droughts[8]. The second work indicates that the intercropping of coffee and macaúba can be an adaptation strategy under future climatic variability, when high temperatures and low rainfall are expected[9].

The harvesting and post-harvesting processes were contemplated in 17 articles. One of them recommends harvesting the fruits directly from the tree, before they fall (pre-abscission stage), or collecting them from the ground up to seven days after their fall (abscission, when fruits separate from the tree). In both cases, fruits should be treated with fungicide prior to storage[10].

[2] (BICALHO et al., 2016) | [3] (CORRÊA et al., 2018) | [4] (SCHLICKMANN-TANK et al., 2020)
[5] (MAIA et al., 2020) | [6] (GUATIMOSIM; PINTO; BARRETO, 2013) | [7] (RAMOS et al., 2001)
[8] (ROSA; SOUZA; PEREIRA, 2019) | [9] (MOREIRA et al., 2018) | [10] (EVARISTO et al., 2016)

Industrial processing

A crucial aspect for the economic feasibility of macaúba oil-based biofuel is the industrial processing of products derived from the species. This study identified 57 articles on methodologies that aim to improve the efficiency of macaúba biodiesel and biokerosene processing.

The 57 articles can be separated into seven themes: esterification (29), prior to esterification (14), after esterification (3), metal surface corrosion (1), biodiesel mixture (2), pyrolysis (5), and other processes (2). Most articles (29) address the efficiency of the esterification process, while 14 deal with the procedures for extracting oil from the mesocarp (pulp) or endocarp (seed). Five researches characterize the content of macaúba biodiesel waste after combustion, while three focus on the purification of the water esterified oil.

Two articles present studies related to the degree of biodiesel in diesel blending. Two focus on other industrial processes, aimed at the production of pies and animal feed. Despite the relevance of the subject, only one article studies the problem of metal corrosion caused by biodiesel[11].

It should be noted that 33 of the 57 examined articles mention the high content of free fatty acids (FFA) in macaúba oils, which makes the species an excellent alternative for biodiesel production.

One of the important findings of this set of research works is the more complete combustion provided by macaúba biodiesel, implying a tendency to reduce emissions when compared to current commercial diesel B. Due to the lower content of polyunsaturated fatty acids, macaúba biodiesel offers greater resistance to oxidation than soybean biodiesel, for example, corresponding to less severe impacts on the engine fuel injection system.

An important topic raised by the articles grouped under "industrial processing" is the use of macaúba almond oil (seed or kernel) in the production of biokerosene. Almond oil presents excellent oxidation resistance, as it consists mainly of saturated organic chains. This stability is inherited by the biodiesel prepared from such oil. The second positive feature of biodiesel prepared from macaúba almond oil is that it presents a low cold filter plugging point (CFPP). Two articles mention blends that use almond oil, concluding on the feasibility of its blending with fossil kerosene.

Three other articles investigate the production of green diesel, drop-in fuel, or renewable hydrocarbons, fuels produced from vegetable oils to be used pure in diesel cycle engines. The most relevant aspect of such fuels is that they can be used in the same engines and machines adapted to fossil diesel. Its manufacturing process – catalytic deoxygenation – is different from that used to obtain ordinary biodiesel.

[11] (BATISTA et al., 2019)

Research on the production of green diesel and biokerosene from vegetable oils, through catalytic deoxygenation, has been underway for decades in several parts of the world.

Uses and benefits of macaúba

The potential use of macaúba parts and extracts was the subject of 80 scientific articles in the survey carried out. The parts comprise epicarp, mesocarp, endocarp, almond and seed, while macaúba extracts are basically oils, pulps, pies and leaf extract.

Almost all articles refer to macaúba as a potential species for biofuel production. Presented in **Table 1**, the uses and products researched were grouped into five sets: industrial products, animal feed, drugs, biofunctions, and cosmetics and cleaning articles (see **Graph 2**).

Graph 2. **Groups of products**

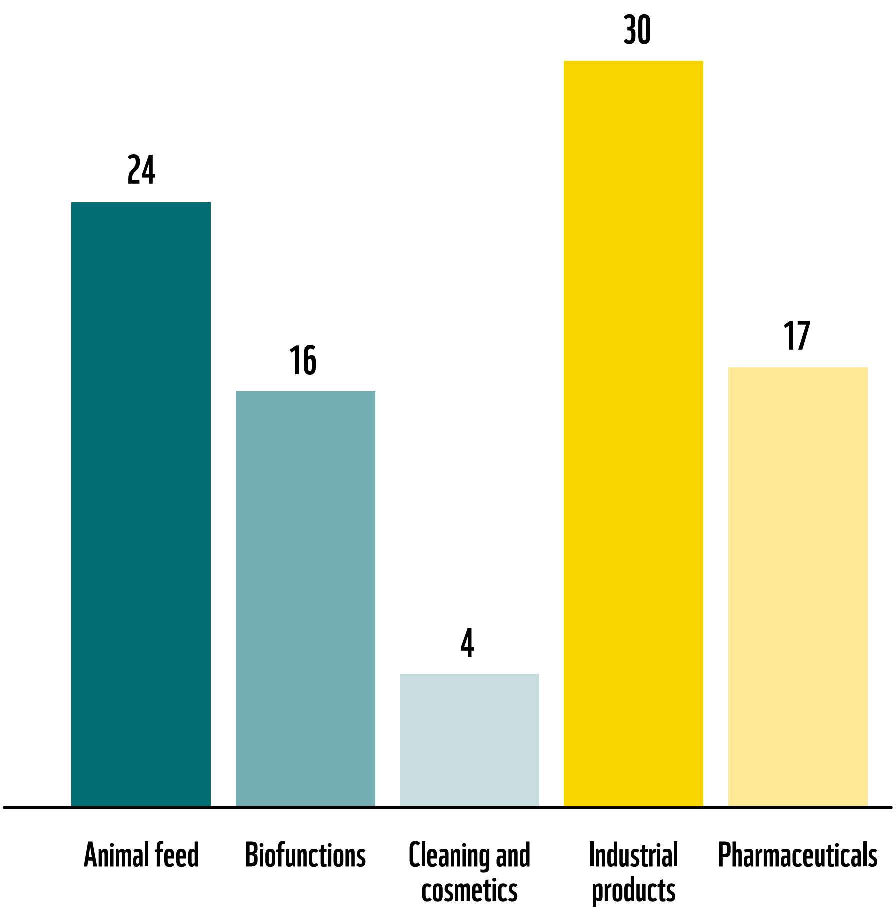


Table 1. Uses and products

Group of products	*Type of product*	*Publications*	*Group (last block)*
Animal feed	Pulp Pie	13	24
	Worm	3	
	Ruminants Ecosystem	6	
	Silage	3	
Biofunctions	Antidiabetic	2	16
	Anti-inflammatory	3	
	Antimutagen	2	
	Antioxidant	7	
	Apoptotic	1	
	Diuretic	2	
	Enzymes	4	
	Hypoglycemic effects	1	
	Immunomodulation	1	
	Other biofunctions	4	
Cleaning and cosmetics	Cosmetics	2	4
	Hygiene products	1	
	Sunscreen	1	
Industrial products	Bio-abrasives	1	30
	Organic absorbent	3	
	Biochar	6	
	Bio composites	1	
	Biofuel	7	
	Bricks and briquettes	2	
	Lignin and cellulose	4	
	Lubricants	1	
	Physico-chemical composition	5	
	Polyurethanes	1	
	Solid biofuel	1	
Pharmaceuticals	Calcium soaps (protective fats)	1	17
	Functional foods and human nutrients	12	
	Pharmacology	3	
	Prebiotics	1	
	Tablet	1	
	Vitamins	3	
Total			80

In the group of industrial products, in addition to liquid fuels (biodiesel and biokerosene), the consulted articles report the use of macaúba in the manufacture of activated carbon intended for the absorption of toxic components in industrial processes. The use of macaúba pie as a component of bricks and tiles indicates alternatives for employment of biofuel industry waste in locations far from industrial centers.

In the animal feed group, the use of pulp pie for the production of feeds and silage has a huge relevance to the economic sustainability of the macaúba business, as the species can be widely cultivated intercropped with extensive livestock throughout the Cerrado.

The groups of biofunctions, drugs and cosmetics refer to more complex applications in the chemical and pharmaceutical industries.

Its implementation in the Brazilian territory would probably require a higher amount of investments compared to the industrial process and animal feed. However, these are industries whose products of higher added value can contribute to the economic feasibility of macaúba production. On the other hand, macaúba oils, extracts, and pulps could be used in already established chemical and pharmaceutical plants.

The more applications are developed for the species, the greater its chance of getting a foothold in the market as feedstock for biofuels, reducing the risk to producers. Under this circumstance, the price paid to the palm suppliers could be formed by more than one industry, in addition to the biofuel industry – ensuring the producer freedom to direct their harvest to a set of customer industries, maximizing their gains.

Other oilseeds for biodiesel production

It is important to note that the scientific articles analyzed present other species of oilseeds in addition to macaúba – baru, belly palm, guariroba, jerivá, and licuri. All of them are palm trees favorable to the production of biodiesel and native to Brazil, except for the belly palm *(Acrocomia crispa)*, which comes from Cuba. They can also be used in the production of animal feed, in human food, and as solid fuel, and can be grown intercropped with extensive livestock raising. In theory, they could be used in the recovery of legal reserves or to enrich biodiversity in degraded pastures, as it occurs with macaúba.

Guariroba and licuri are promising options for the Caatinga, and jerivá could contribute to diversify oil production in the Cerrado. As for babassu *(Orbygnia spp; Attalea speciosa)* and buriti *(Mauritia Flexuosa)*, they represent auspicious alternatives for the mid-north, in the contact range between the Cerrado and the Amazon biomas[12].

Researchers from the Federal Universities of Rio de Janeiro and Fluminense, from the Federal Institute of Maranhão, and the National Institute of Energy and Environment Science and Technology studied the technical feasibility of producing biodiesel using vegetable oils, with high contents of free fatty acids, from the following native Brazilian species: Brazil nut *(Bertholletia excelsa)*, babassu (*Orbignya speciosa*), pequi fruit *(Caryocar brasiliensis)*, palm *(Elaeis guineenses)* and macaúba *(Acrocomia aculeata)*. They concluded that it is possible to adapt biodiesel production procedures to such oils[13].

Authors and research institutions

The Federal University of Viçosa (UFV) leads the ranking of scientific production on macaúba, with 30% of articles published in 11 of the 12 research areas under the classification used for this publication. **Table 2** shows the institutions with more than 5% of articles published on macaúba by 2020. In addition to those, 126 other institutions participated in the research, contributing with less than 5% of the articles. 83 of them are based in Brazil.

We also verified that Brazilian researchers participated in almost all published articles, 94%, demonstrating that knowledge is being developed essentially by autochthonous researchers and institutions, including all research related to industrial processes.

[12] Information on babassu and buriti can be found in the Federal University of Viçosa biofuel material.
[13] (VIEIRA et al., 2018)

Table 2. Research institutions

Institution code	Institution name	% Published articles
UFV	Universidade Federal de Viçosa	30.45%
UFMG	Universidade Federal de Minas Gerais	23.64%
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária	13.64%
UNIMONTES	Universidade Estadual de Montes Claros	9.09%
UEM	Universidade Estadual de Maringá	8.64%
UFLA	Universidade Federal de Lavras	7.73%
USP	Universidade de São Paulo	6.36%
UNB	Universidade de Brasília	5.91%
UFGD	Universidade Federal da Grande Dourados	5.45%
UFMS	Universidade Federal do Mato Grosso do Sul	5.45%

Research funding

The research reported in the articles found in the Web Of Science was almost entirely funded by Brazilian research agencies, namely, the research support state foundations (FAPs), the National Council for Scientific and Technological Development (CNPq), and the Coordination for the Improvement of Higher Education Personnel (Capes).

It is important to emphasize the interest of the Brazilian State in the development of the vegetable oils sector, especially in the development of biofuels, as occurred in the research for creating the technology for producing ethanol from sugarcane.

03.

LEGISLATION

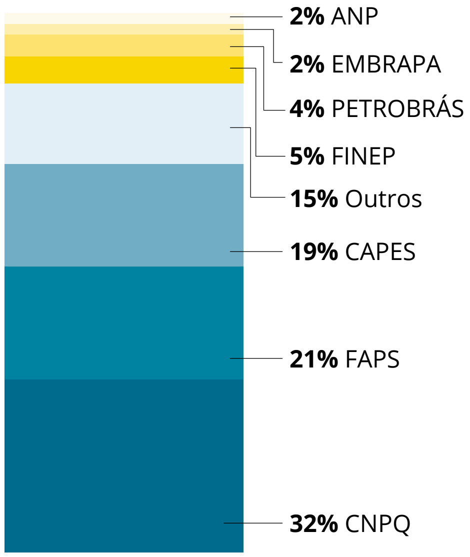
There has been an evolution in the addition of biofuel to diesel since Law No. 11,097/2005 established the mandatory use of biodiesel in fossil diesel. In Article 4, the law defines biodiesel as "biofuel derived from renewable biomass, for use in compression ignition internal combustion engines (diesel cycle engines) or, according to regulation, for generation of another type of energy able to partially or totally replace fossil originated fuels".

In 2004, ANP Resolution No. 42/2004 specified that biodiesel would be fuel "composed of alkyl esters of long chain fatty acids, derived from vegetable oils or animal fats, according to specification (...)". Fatty acid esters are obtained from the reaction between triglycerides or fatty acids and alcohol, in the presence of a catalyst. And this is the case of biodiesel obtained from macaúba oil and other Brazilian oilseeds, such as soybeans.

Just over three months after the adoption of the Paris Agreement, on December 12, 2015, National Congress approved Law No. 13,263/2016, which authorized the National Council for Energy Policy (CNPE) to increase the percentage of biodiesel blending to the level of 15%, provided that the conditions for tests approval in engines are met.

Researchers' interest in macaúba increased as CNPE expanded the compulsory minimum percentage of biodiesel in the fuel blend for the diesel cycle engine **(Graph 3)**.

Graph 3. **Funding Agencies**



In addition to that, the establishment, in the last ten years, of national and international definitions and standards regarding production processes and composition of biodiesel facilitated the development of research on procedures that enable meeting such definitions and standards. Among them, it is worth mentioning ANP Resolution No. 45/2014, the standards of the European Committee for Standardization (CEN – Comité Européen de Normalisation) for HVO (Hydrotreated Vegetable Oil), and national specifications for alternative aviation kerosene.

Despite the regulations of the National Agency for Petroleum, Natural Gas and Biofuels (ANP) restricting the name biodiesel to fatty acid esters, there are other fuels of renewable origin available in the world market that can be used in diesel cycle engines, according to Law No. 11,097/2005. However, as seen in the previous chapter, much of the research applied to macaúba focuses on the production of esters from fatty acids.

The main destination of biodiesel is the blending in diesel in increasing proportions. ANP Resolution No. 50/2013 regulates the specifications of diesel oils for road use, considering the need to meet the seventh stage of the Air Pollution Control Program by Motor Vehicles (Proconve P7) [14]. Art. 7 establishes that *"diesel fuel B for road use marketed in the country must contain biodiesel in a percentage determined by current legislation"*.

The mandatory addition of biodiesel in 2020 was stipulated at 12%, with an increase to 15% in 2023 as legally provided. While the proportions of biodiesel in the diesel blend increased, Brazil demanded increasingly restrictive standards in relation to emissions. Research and agreements between engine manufacturers and government entities that determine the specifications of biofuels have also advanced. The mandatory addition of biodiesel reached 13% at the beginning of 2021; however, the increase in soybean prices and, later, the increase in diesel prices led to a reduction in the mandatory content to 10%.

Another incentive to biodiesel came from Law No. 13,576/2017, which established the National Biofuels Policy (RenovaBio), acknowledging the strategic role of biofuels in the national energy matrix and the importance of fuel supply security and greenhouse gas emissions mitigation. RenovaBio started to be implemented effectively in 2020, with fuel distributors being obliged to meet the annual decarbonisation goals.

[14] Vehicle emissions control program created in 1986 by Conama with the objective of reducing and controlling atmospheric contamination and noise emission by mobile sources. P7 is the seventh standard published in 2012, equivalent to the European standard of 2008.

04.

BIODIESEL MARKET

Biodiesel is biofuel obtained from the conversion of vegetable oils extracted from oilseeds such as soybean, cotton, palm, and sunflower, among others, or from animal fat of cattle, pigs and poultry. After undergoing transformation and purification processes to comply with quality specifications, it is intended for application in diesel cycle engines as partial or full replacement of mineral origin diesel (diesel A)[15].

Brazil has a long experience with the use of biofuels in the transport sector. In 1931, President Getúlio Vargas's decree forced gasoline importers to add 5% of alcohol to fossil fuels. It was, however, the National Alcohol Program (Proálcool), launched by the federal government in 1975, that consecrated ethanol produced from sugarcane as one of the structural parts of the Brazilian fuel market.

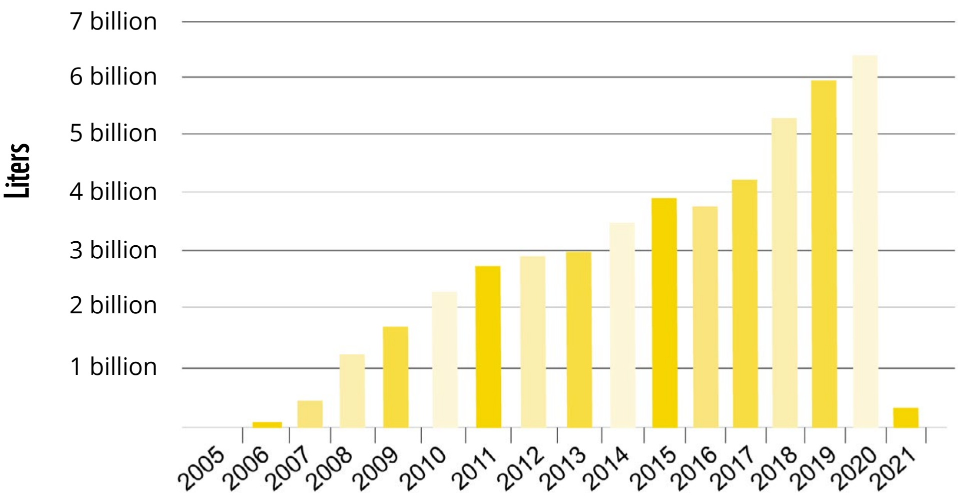
Another fundamental step to expand the use of biofuels in the country was taken in 2005, when Law No. 11,097/2005 established the first regulatory framework for biodiesel in Brazil.

The law provided for the definition of deadlines for addition of biodiesel to diesel oil at minimum mandatory percentages. Between the beginning of the National Program for the Production and Use of Biodiesel (PNPB), in 2005, and December 2019, more than 40.6 billion liters of this biofuel were produced[16].

Biodiesel

In 2010, the Ten-Year Energy Expansion Plan (PDE) prepared by the Energy Research Company (EPE) for the period 2010-2019 estimated the consumption of 3.8 billion liters of biodiesel in 2020. At the time of its publication, PDE considered that Brazil would face difficulties to comply with Law No. 11,097/2005, given the limited production capacity to meet the mandatory percentage of 5% of biodiesel in the diesel blend. However, biodiesel production and consumption reached 6.8 billion liters in 2020 (see **Graph 4**). At such level, Brazil became the third producer of biodiesel, with 12% of the world production, behind only the United States and Indonesia.

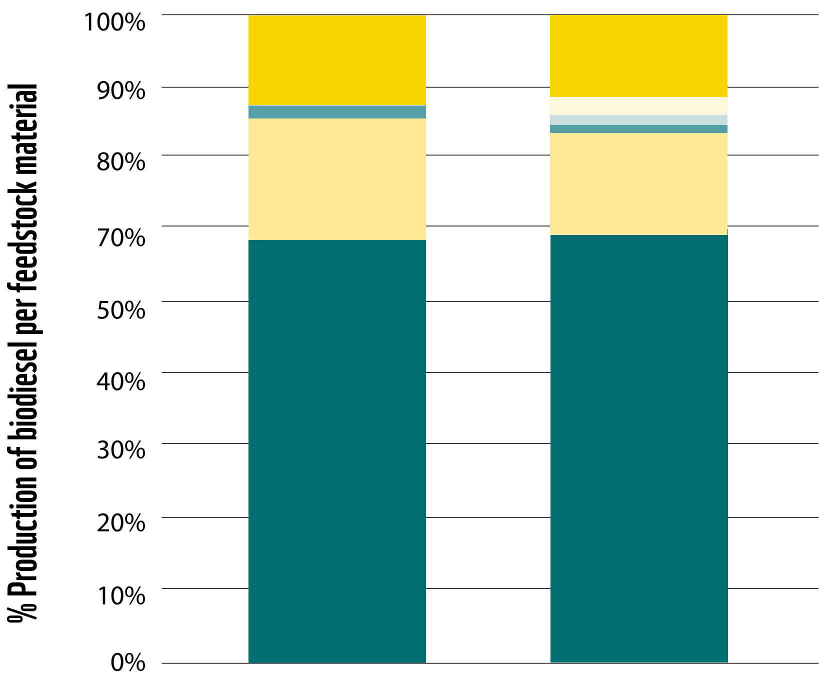
Graph 4. Consumption of Biodiesel in Brazil



[15] (ABIOVE, 2021).
[16] (EPE, 2020).

In the first 15 years of biodiesel commercial use in the country, the demand for biodiesel was met using mainly soybean, the only oilseed available on the necessary scale to meet the legislation established in 2005. Since 2008, soybean has been feedstock for the production of 70% of Brazilian biodiesel **(Graph 5)**. It should also be noted that only 3.7% of the soybean production in 2019 (120 million tons of grains) was directed to the biodiesel industry.

Graph 5. Production of biodiesel per feedstock



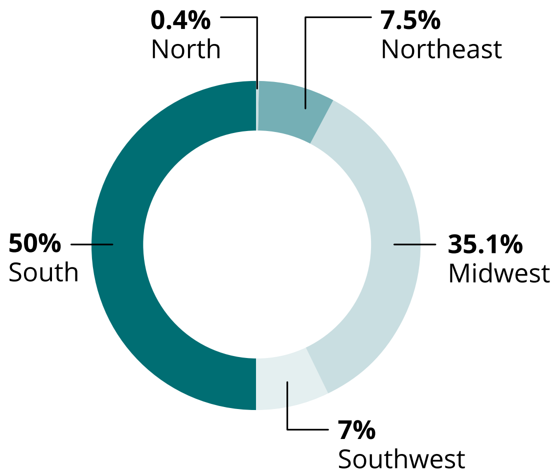
In cubic meter (m^3):

	2008	2020
Other fatty materials	140,489	739,735
Various feedstock	0	185,138
Used frying oil	0	79,023
Cotton oil	18,353	107,193
Animal fat	206,966	740,755
Soybean oil	801,320	4,580,193

Source: data by ABIOVE, graph by Author

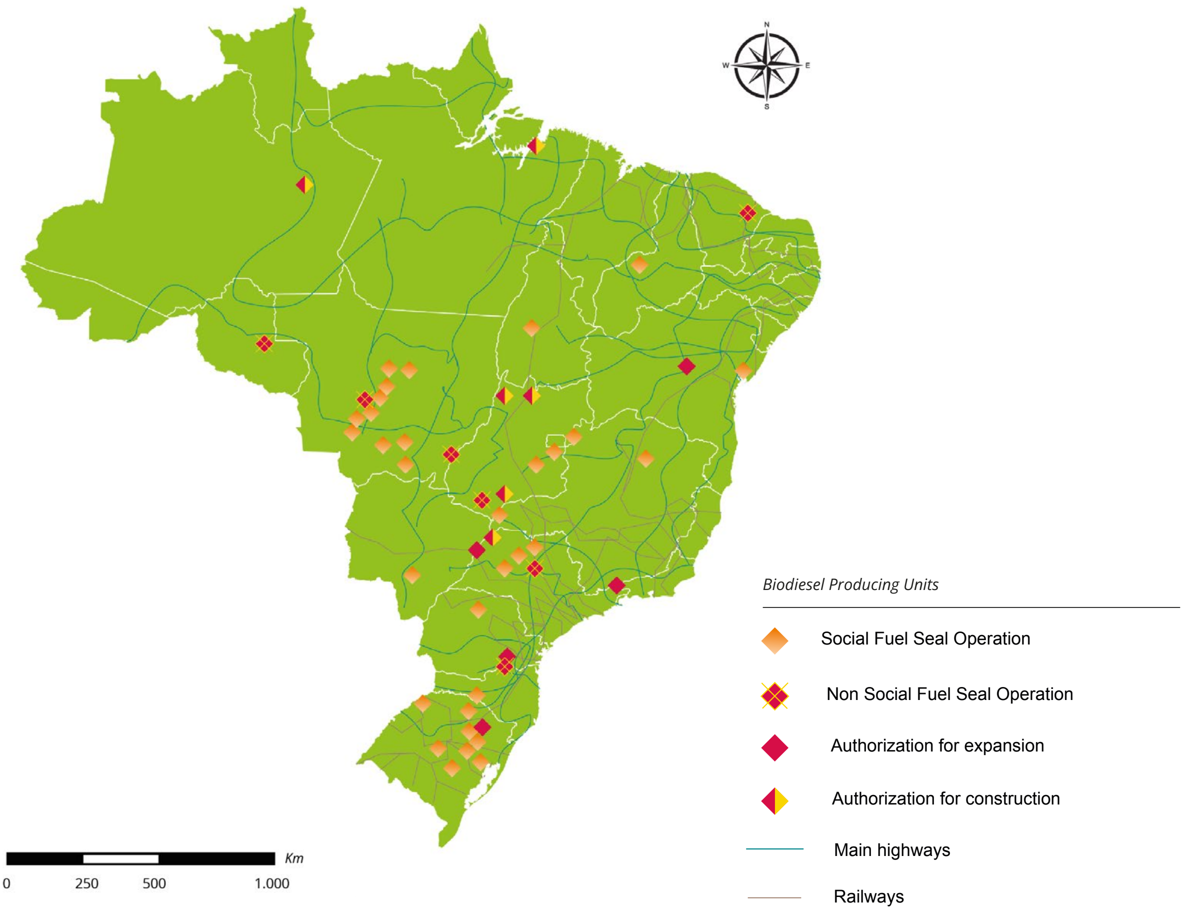
However, production is very concentrated in the South and Southeast regions **(Graph 6)**, with the first producing half of Brazilian biodiesel. There is potential to diversify biodiesel processing in the country because EPE authorized biofuel plants are well distributed in the South, Southeast and Midwest regions **(Graph 7)**.

Graph 6. Regional participation in biodiesel production in 2021



Source: ABIOVE, 2021

Graph 7. Authorized biodiesel producers in 2020

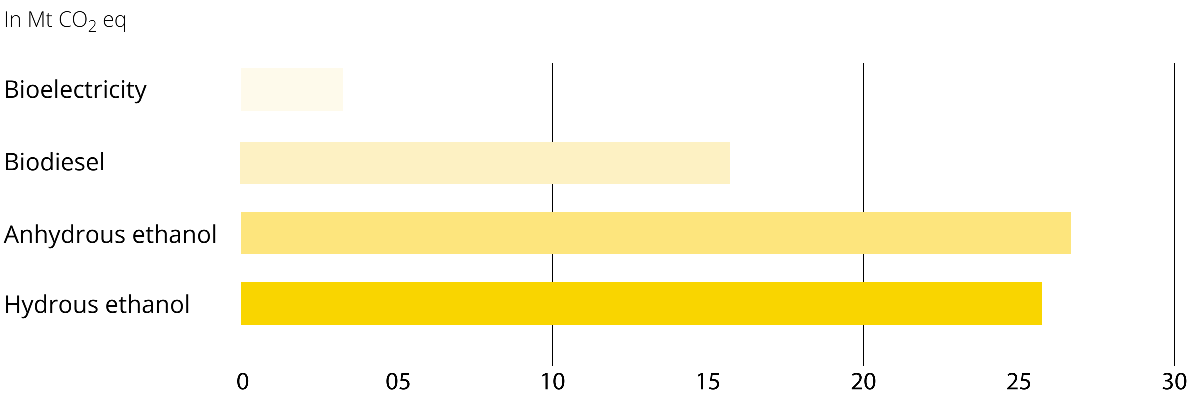


Fonte: MME-EPE (2020)

The challenge in this scenario will be diversifying the sources of feedstock to take advantage of degraded or underutilized areas, reduce the risk of investments in the business, maximize gains through intercropping macaúba and other palm trees with extensive livestock raising, and promote increased income for small producers and family farming. Different reasons justify the need to diversify the mix of feedstock and better distribute these biofuel plants in the Brazilian territory. The most relevant reason is the reduced risk of non-compliance with the obligation to replace fossil fuels. In 2020 and 2021, for example, the increase in the price of soybean due to greater demand for oilseed from the international market made the government decrease the percentage of biodiesel in the diesel blend. There were four reductions between January and September 2021, which decreased from 13% to 10% the share of biodiesel blended in diesel.

A second reason is that the expansion of biodiesel use contributes to the reduction of CO_2 emissions, in line with the commitment made by Brazil in the Paris Agreement. The addition of biodiesel to diesel avoided the emission of 16.5 million tons of CO_2 in 2019[17], a significant amount when considered to be equivalent to 61% of the 27.1 million tons of CO_2 avoided due to the blend of anhydrous alcohol in gasoline. Adding up all biofuels, Brazil spared the emission of 69.9 million tons of CO_2 in 2019 **(Graph 8)**.

Graph 8. GHG emissions avoided with biofuels in 2019



Source: EPE, 2019

The projections of PDE 2030 were considered to simulate the future demand for biodiesel, which is estimated at 11.5 billion liters in 2030.

If such demand continues to be met in 70% by soybean, 7.45 million tons of soybean oil will be required, considering the average production of 1,081 liters of biodiesel per ton of soybean oil. The volume would come from the processing of 39 million tons of the oleaginous grains, harvested in an area of 11 million hectares, assuming a productivity of 3.5 tons per hectare.

[17] (EPE, 2020).

However, only 2 million hectares would be needed to meet the demand if biodiesel production came from macaúba[18]. For this calculation, the conservative productivity data of 4,000 liters of oil per hectare, published by the research, was used. The authors emphasize that this would be the area necessary to meet only 15% of the biodiesel percentage established in CNPE Resolution 16/2018.

Green diesel

It is also possible to diversify the supply of biofuels with products such as green diesel, also known as renewable diesel, distinct from ester-based biodiesel. Although chemically similar to mineral diesel, renewable diesel has vegetable or animal origin and can replace fossil diesel entirely (pure use) or partially. As it has no metallic contaminants, it is compatible with vehicle technologies.

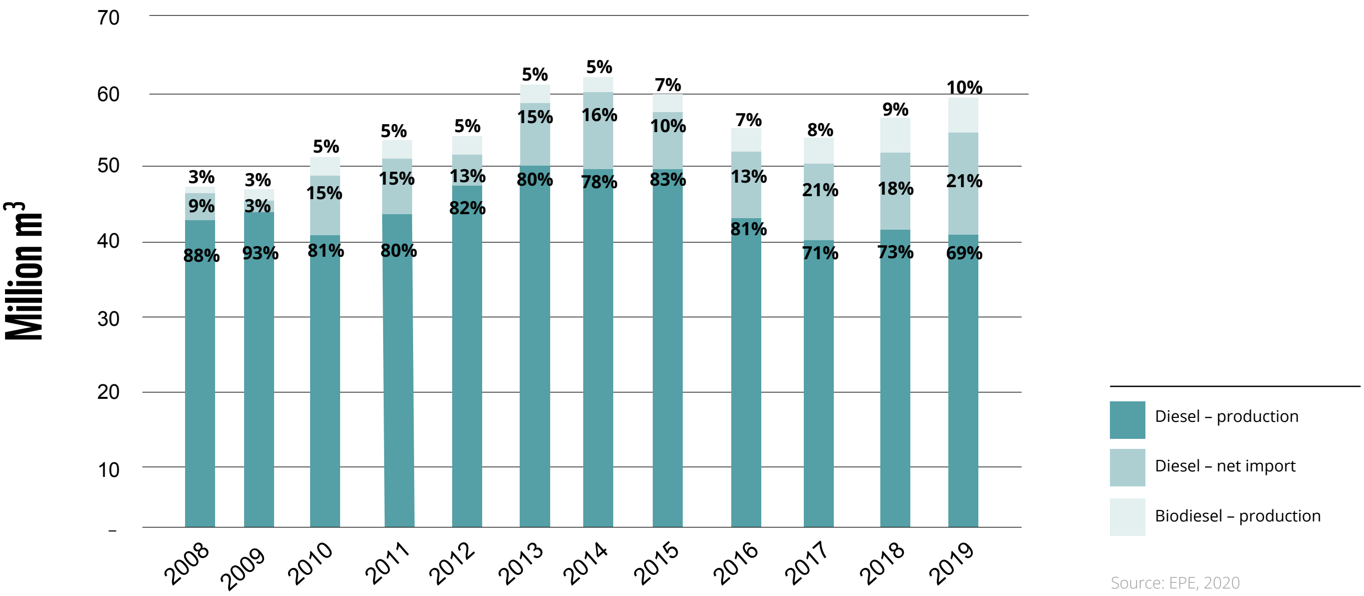
Renewable diesel, although unprecedented in Brazil, is used in Europe and the United States. It is the third most produced biofuel in the world19, even if with modest volumes: in 2019, 6.5 billion liters were produced, compared to 47 billion liters of biodiesel.

At the beginning of 2022, the diesel consumed in Brazil had 10% of renewable content coming from ester-based biodiesel added to mineral diesel. There is a proposal under discussion so that renewable diesel can also be added to mineral diesel, contributing to meet the emission requirements of Proconve P8 phase. The new phase of the program will be introduced throughout 2022 and 2023, requiring the same emission limits in force in the United States and Europe.

One of the types of renewable diesel is HVO (Hydrotreated Vegetable Oil), derived from the hydrogenation of residual oil of soybean and palm, and animal fat, among others. HVO has greater storage stability and can be used in diesel engines without the blending percentage limits required by fatty acid ester (biodiesel).

According to EPE and ANP, Brazil has been gradually increasing diesel import since 2016 to completely supply the domestic market (see **Graph 9**). The share of imported diesel reached 21% of the total diesel consumed in 2019, exceeding the mark of 13 billion liters, dropping back to almost 12 billion liters in 2020, according to ANP.

Graph 9. Production and import of diesel



Source: EPE, 2020

[18] These calculations were made based on the indicators raised by the authors and considering macaúba production in intercropped areas with pastures.

[19] (REN21, 2020).

If the country completely replaced imported diesel with renewable diesel, it would save around R$24 billion in foreign currency at 2021 prices, and would practically double the savings if the price of a diesel barrel reached US$ 100 in 2030, according to estimates by EPE.

To produce 12 billion liters of green diesel (equivalent to the diesel imported in 2020), it would take just over 6 million hectares for macaúba planting. The full replacement of fossil diesel with renewable diesel in 2030 would expand the area cultivated with macaúba to 26 million hectares.

Aviation fuel

The aviation industry has committed to zero its net greenhouse gas (GHG) emissions by 2050. Sustainable aviation fuel (SAF), such as aviation biokerosene (BioQAV), is the most relevant factor in the set of measures to reduce emissions of the sector, which also include technological development and operational improvements[20].

In addition to establishing quality standards and sustainability criteria to characterize a product as SAF, the International Civil Aviation Organization (ICAO) fosters the development of sustainable aviation fuels[21] and supports its member countries in the formulation of action plans to reduce international aviation CO_2 emissions.

In Brazil, there are initiatives that encourage aviation biofuels research, industrial development, and market, such as the Brazilian Network of Biokerosene and Renewable Hydrocarbons for Aviation (RBQAV), and the Biokerosene and Renewables Mining Platforms of Minas Gerais and Zona da Mata.

In the legislative sphere, Law No. 14,248/2021 was enacted in November 2021, creating the National Biokerosene Program to encourage research and promotion of biomass-based energy production, aiming at the sustainability of Brazilian aviation by using clean technologies.

The world production of SAF jumped from less than 1 million liters in 2015 to 7 million liters as of 2016, following the adoption of the Paris Agreement in December 2015, when the commitments to cut emissions of GHG were communicated to the UN by the treaty member countries. Since then, production has been growing significantly. In 2019, at the seminar organized by ICAO on sustainable aviation fuels (SAF), participants concluded that there is already production capacity for the coming years of up to 8 million liters. Meanwhile, the plans of the airline industry are even more ambitious. The Roundtable on Sustainable Biomaterials (RSB)[22] states that airlines have made offtakes totaling over 6 billion liters and the demand for aviation fuel increases from 1.5% to 3% each year.

By 2040, the global demand for aviation fuel estimated by ICAO should reach 533 billion liters[23]. In a scenario in which Brazil produces SAF to meet 12% of this demand[24], it would be necessary to increase its production to 64 billion liters in the next two decades, which would imply expanding the cultivation of oilseeds for the processing of biofuels to 43 million hectares.

[20] (ZUCKERMAN; QUIQLEY; MACFARLANE 2015).
[21] (ICAO, 2017).
[22] (RSB, 2020).
[23] (ICAO, 2017).
[24] In equivalent proportion to the current participation of Brazil in the world production of biodiesel.

05.

PRIORITY AREAS FOR PLANTING MACAÚBA

The recovery of degraded pastures in Brazil has evolved positively in the last 20 years, according to data from Mapbiomas[25]. After analyzing 35 years of satellite images – between 1985 and 2020 – Mapbiomas verified a drop in areas with signs of degradation from 70% in 2000 to 53% in 2020. In the case of severely degraded pastures, there was an even more significant reduction: they represented 29% of pastures in 2000 (46.3 million hectares), declining to 14% (22.1 million hectares). Improvement was identified in all biomes. Greater retractions were found in the severely degraded areas of the Amazon (60%), Cerrado (56.4%), Atlantic Forest (52%) and Pantanal (25.6%).

As previously reported, macaúba has the potential to recover degraded areas and improve water retention in the soil. Observing the pasture quality evolution map, the analysis prepared for this publication identified four priority areas for planting macaúba, based on the following criteria:

- Access infrastructure – roads and proximity to consumer centers;

- Higher probability of rural producers' interest in the cultivation project of this palm tree.

Table 3. Municipalities of priority areas

Region	Municipalities		
(1) MS – Southwest	Aquidauana	Miranda	Porto Murtinho
	Bela Vista	Nioaque	Rio Negro
	Bonito	Dois Irmãos	Rochedo
	Caracol	Guia Lopes Da Laguna	Sidrolândia
	Corguinho	Maracaju	Terenos
(2) MS East – GO South	Água Clara	Itarumã	Paranaíba
	Anaurilândia	Jataí	Quirinópolis
	Aparecida do Taboado	Nova Andradina	Ribas do Rio Pardo
	Aporé	Cassilândia	Santa Rita do Pardo
	Brasilândia	Chapadão do Sul	Selvíria
	Cachoeira Alta	Inocência	Serranópolis
	Caçu	Itajá	Três Lagoas

[25] (MAPBIOMAS, 2021).

Region	Municipalities		
(3) Goiás	Abadiânia	Goianápolis	Nova Veneza
	Adelândia	Goianésia	Palmeiras De Goiás
	Americano Do Brasil	Goianira	Palminópolis
	Anápolis	Goiás	Paraúna
	Anicuns	Guapó	Petrolina De Goiás
	Aparecida De Goiânia	Heitoraí	Piracanjuba
	Araçu	Hidrolândia	Pirenópolis
	Aragoiânia	Indiara	Pontalina
	Avelinópolis	Inhumas	Professor Jamil
	Avelinópolis	Ipiranga De Goiás	Rubiataba
	Bela Vista De Goiás	Itaberaí	Sanclerlândia
	Bonfinópolis	Itaguari	Santa Bárbara De Goiás
	Brazabrantes	Itaguaru	Santa Isabel
	Caldazinha	Itapaci	Santa Rosa De Goiás
	Campestre De Goiás	Itapuranga	Santo Antônio De Goiás
	Caturaí	Itauçu	São Luís De Montes Belos
	Ceres	Jandaia	São Luiz Do Norte
	Cezarina	Jaraguá	São Patrício
	Corumbá De Goiás	Leopoldo De Bulhões	Senador Canedo
	Damolândia	Morro Agudo De Goiás	Trindade
	Edealina	Mossâmedes	Turvânia
	Edéia	Nazário	Uruana
	Firminópolis	Nerópolis	Varjão
(4) Mato Grosso	Água Boa	Juscimeira	Poxoréu
	Barra Do Garças	Nossa Senhora Do Livramento	Ribeirão Cascalheira
	Cáceres	Nova Xavantina	Rondonópolis
	Campinápolis	Novo São Joaquim	Santa Rita Do Trivelato
	Campo Verde	Paranatinga	Santo Antônio Do Leverger

Region 1 (Mato Grosso do Sul - Southwest)

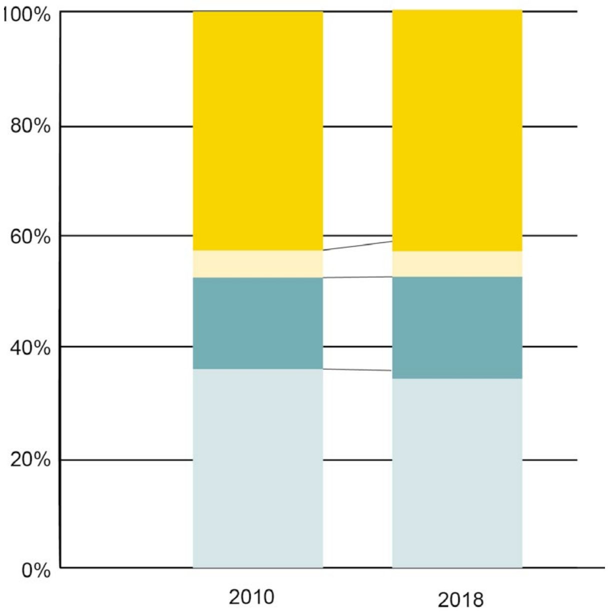
Native vegetation cover did not decrease, pasture areas were converted to crops and 14% of degraded pastures was recovered. The region has potential aptitude for introduction of a new culture such as macaúba.

Region 2 (East of Mato Grosso do Sul - South of Goiás)

Vegetation cover area has grown with forests planted to supply a new pulp mill in the region. There was also expansion of agricultural area – two new enterprises reduced the space of pastures and occupied extensions of degraded pastures.

Graph 10. Southwest of MS Region

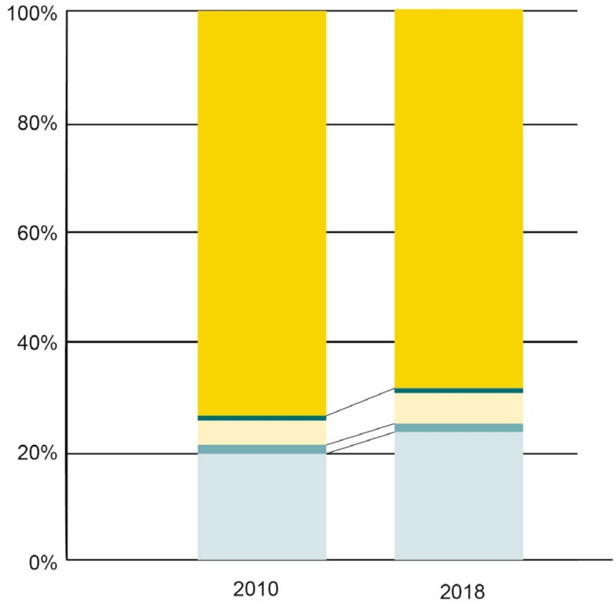
In hectare (ha)



Land use	*2010*	*2018*
Pastures	3,443,513	3,275,156
Mosaic	2,915	3,017
Agriculture	447,705	714,139
Non Forest Natural	1,186,175	1,131,193
Forest	2,868,101	2,820,688

Graph 11. East of MS Region - South of GO

In hectare (ha)



Land use	*2010*	*2018*
Pastures	7,488,075	6,820,947
Mosaic	65,794	56,034
Agriculture	612,211	943,889
Non Forest Natural	260,241	261,918
Forest	2,173,939	2,503,884

Region 3 (Goiás)

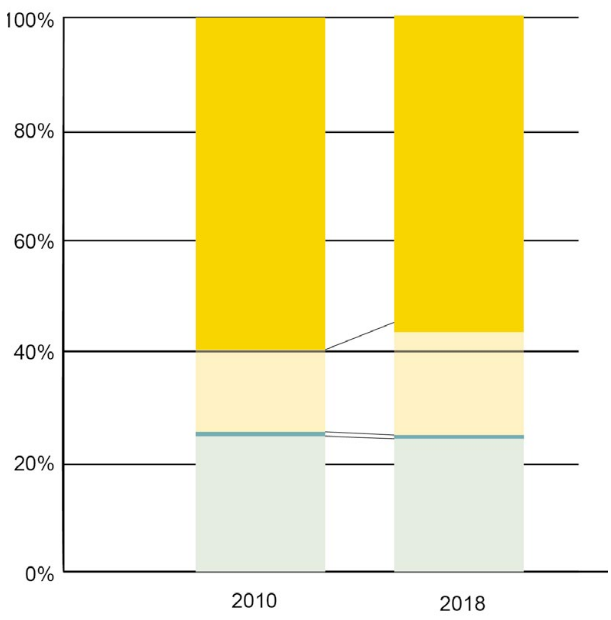
Agriculture gained more space without shrinking the surface covered by native vegetation. The advance of crops occurred to the detriment of pastures, including their degraded portion.

Region 4 (Mato Grosso)

Native vegetation cover decreased by 340 thousand hectares and pasture area by 350 thousand hectares (including degraded pastures), expanding the area occupied by agriculture.

Graph 12. Goiás Region

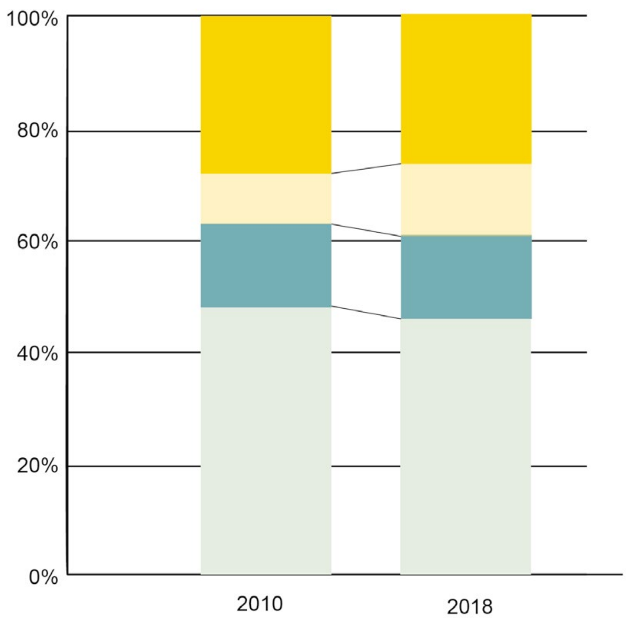
In hectare (ha)



Land use	2010	2018
Pastures	2,728,621	1,111,214
Agriculture	504,748	805,127
Non Forest Natural	66,832	60,818
Forest	1,135,795	1,111,214

Graph 13. Mato Grosso Region

In hectare (ha)



Land use	2010	2018
Pastures	4,789,786	7,898,873
Agriculture	1,578,817	2,298,561
Non Forest Natural	2,611,242	2,569,626
Forest	8,239,607	7,898,873

In common, all the mentioned regions have a high potential of interest in the introduction of a new crop that may contribute to the recovery of pastures.

06.

ECONOMIC AND FINANCIAL FEASIBILITY OF INTERCROPPED MACAÚBA

The study considered three formats of macaúba production: in an integrated crop-livestock-forest system (CLF), as native species in legal reserve areas to be recovered, and in monoculture. Among them, the CLF system presented the best balance between socio-environmental benefits and producer attractiveness. Thus, a cash flow analysis was prepared to estimate the economic and financial feasibility of the production, a fundamental aspect to assess the large-scale supply capacity of macaúba for biofuel production.

Average costs for typical activities were considered, and conservative estimates for greater uncertainty values were adopted. The values of the basic products of the CLF system are as follows. The other assumptions are in the annex.

Product	*Amount*
Macaúba	R$ 200.00/ton
Livestock	R$ 318.00/@
CO_2 removed	R$ 10.00/ton
Corn	R$ 1.604.00/ton

The cash flow analysis estimated the operational internal rate of return (IRR) at 11.52% p.a. before taxes, and 4.63% p.a. including taxes. These calculations admit zero inflation, a situation in which there is no readjustment of costs or prices.

If inflation of 10%p.a. is considered, the operational IRR obtained is 22.68% p.a., and 15.78% after taxes. It is important to bear in mind that this estimate assumes that both costs and prices of products vary uniformly, something unlikely in reality.

Among the possible sensitivity analyses, it is interesting to observe how the IRR varies compared to carbon credit prices:

Carbon credit price	*Operational IRR (% p.a. – zero inflation)*
10.00	11.52
15.00	13.19
20.00	14.90
25.00	16.65

It is noted that in a sale of carbon credits for an amount of US$ 5.00/ton, a perspective considered conservative by specialists dealing with carbon markets, it is possible to obtain an IRR greater than 16.65% per year.

07.

CONCLUSIONS

The expansion of sustainable biofuels supply can be reached without the occupation of new areas, through the adoption of intercropped macaúba in degraded or underutilized pastures. This strategy has the benefit of promoting product diversification and, consequently, the economic resilience of properties, while increasing the provision of ecosystem services.

Macaúba is the species with lowest technical and economic risk among candidates to supply feedstock for biodiesel and biokerosene production, given that research on that culture, which is already subject of many small ongoing projects, is well advanced. It can be widely cultivated in the Cerrado, mainly intercropped with extensive pastures, achieving satisfactory productivity. Research has also indicated that the trend is to increase pasture productivity, since macaúba contributes to the improvement of soil structure, increased infiltration of rainwater and water retention due to its root system.

In addition to biodiesel and biokerosene, it is possible to produce excellent quality pies and feed for animals, food products, pharmaceuticals and various cosmetics. In this way, macaúba can contribute to the introduction of agribusiness in regions whose economies are not so dynamic and poverty indicators are high, promoting income and jobs generation.

The economic and financial feasibility of adopting intercropped macaúba is highly influenced by the carbon captured and the value earned from it. For this reason, macaúba becomes increasingly attractive as voluntary and mandatory carbon markets consolidate.

To contribute to the recovery of degraded areas and improvement of ecosystem services while supplying several industries and increasing producer resilience, actions should be assessed to encourage production and consolidate the chains that use macaúba.

08.

ANNEX

Planning the financial flow of macaúba producers

For this publication, Atrium Forest Consulting has prepared an Excel spreadsheet to assist the producer in planning the cash flow of the macaúba product. The spreadsheet considers all resources arising from the sale of macaúba fruit, livestock, corn and carbon credits as producer's revenue, and was prepared for use by producers integrated or not to an oil processing industry focused on biodiesel production.

Table 4. Estimated production cost of macaúba in Zona da Mata Mineira

Macaúba – Estimated unit cost of production in R$ per hectare

Medium tech level	Period	Bunch	Kg/Bunch	Kg/Plant	Total/ha
Spacing: 5 x 5 = 400 plants/ha	Year 1	–	–	–	–
Reference region: Zona da Mata, MG	Year 2 to 4	–	–	–	–
Reference soil: Latosol	Year 5 to 10	3.5	12	41	16.380
Module: 5 ha	> 11 years	3.5	18	61	24.500

Description	Specification	UV (R$)	Deployment Year 1		Formation Year 2 to 4		Growing Production Year 5 to 10		Stable Production Year 11 to 30	
A – Mechanized operations			Total		Total count		Total count		Total count	
A1 - Soil preparationPitting	pitting machine	5.00	8.00	40.00						
A2 – Deployment Seedling distribution	MH Tp 75hp+trailer	50.00	2.00	100.00						
A3 – Crop Handling Fertilization (2x)	MH Tp 75hp+trailer	50.00	2.00	100.00	1.00	50.00	50.00	50.00	1.00	50.00
A4 – Harvest Transportation	MH Tp 75hp+trailer	50.00					3.00	150.00	4.00	200.00
Subtotal A				**240.00**		**50.00**		**200.00**		**250.00**
B – Manual operations										
B1 - Soil preparation										
Ant control (4x)	Man-day	40.00	1.00	40.00						
Mowing	Man-day	40.00	1.00	40.00						
Prep. Est./demar.holes	Man-day	40.00	1.00	40.00						
Weed control	Man-day	40.00	2.00	80.00						
Seedling distribution	Man-day	40.00	3.00	120.00						
Pitting+fertilization	Man-day	40.00	5.00	200.00						
Planting	Man-day	40.00	1.00	40.00						
B2 – Crop Handling										
Herb. Weed Control (2x)	Man-day	40.00	2.00	80.00	2.00	80.00	2.00	80.00	2.00	80.00
Leaf pruning	Man-day	40.00					1.00	40.00	1.00	40.00
Fertilization (2x)	Man-day	40.00	2.00	80.00	2.00	80.00	2.00	80.00	2.00	80.00

Description	Specification	UV (R$)	Deployment Year 1		Formation Year 2 to 4		Growing Production Year 5 to 10		Stable Production Year 11 to 30	
B3 – Harvest										
Harvest	R$/ton	40.00					7	262.08	10	392.00
Subtotal B				720.00		160.00		462.08		592.00
C – Inputs										
C1 – Fertilizers										
Limestone	R$/ton	90.00	0.20	18.00			0.20	18.00	0.20	18.00
P: (Soluble phosphate)	R$/ton	550.00	0.15	88.00	0.08	44.00	0.12	66.00	0.24	132.00
N: (Urea)	R$/ton	950.00	0.04	38.00	0.08	76.00	0.12	114.00	0.24	228.00
K: KCl	R$/ton	1700.00	0.04	68.00	0.08	136.00	0.12	204.00	0.24	408.00
FTE Micronutrients	R$/Kg	2.00	10.00	20.00	10.00	20.00	20.00	40.00	30.00	60.00
C2 – Phytosanitary										
Fungicide	R$/Liter	90.00					1.00	90.00	1.00	90.00
Insecticide	R$/Liter	90.00					1.00	90.00	1.00	90.00
Ant Control	R$/kg	5.00	4.00	20.00	2.00	10.00				
C3 – Herbicides										
Post-emergent	R$/Liter	18.00	2.00	36.00	2.00	36.00	2.00	36.00	2.00	36.00
C4 – Seedlings										
Seedlings 1 year	R$/Unit	6.00	400.00	2400.00						
Subtotal C				2688.00		322.00		658.00		1062.00
D – Adm/Commercialization										
Project	2% deployed	2.0%	3700	74.00						
Taxes	% evenue	2.3%					1.00	64.05	1.00	95.80
Subtotal D				74.00		0.00		64.05		95.80

Total Cost (A+B+C+D)		**R$/ ton**	**Year 1**	**Year 2 to 4**	**Year 5 to 10**	**Year 11 to 20**
Total cost	(R$/ha year)		3.722.00	532.00	1.384.13	1.999.80
Revenues*	(R$/ha year)	170.00			2.784.60	4.165.00
Ton average cost	(R$/ha year)	97.94				
Net profit	(R$/ha year)		(3.722.00)	(532.00)	1.400.47	2.165.21

* Average price paid by extractive industries of MG (Comparative: Average price of palm oil ton in 2007 = R$ 160.00 Agrianual 2008)
**1 bunch with 260 fruits x 45 grams each = 12Kg
***1 bunch with 350 fruits x 50 grams each = 18Kg
All values are expressed in Reais per ha (R$/ha)
HM Tp 75hp+trailer = Hour machine, 75hp tractor + 4 ton trailer
Man-day = Value of daily labor (included charges, etc.)

In the model used in the spreadsheet, corn is produced in the first four years of the macaúba project, whose fruits begin to appear in the fifth year. Livestock is removed from the area for the first five years. It should be noted that carbon removals from the atmosphere are higher in the macaúba growth phase (first four years) and that macaúba productivity values still differ substantially among the sources consulted for this analysis. The most conservative reference for crop productivity was used in this publication.

For the calculation of expenses, the national average profitability of livestock (8.8%) and corn (25%) was used. Expenditure on the harvest of macaúba only begins in the fifth year, when it begins to produce, and will grow due to productivity increase.

The productivity estimate used in the cash flow spreadsheet follows the projection in related literature[26]. Meat production from livestock also only starts in the fifth year in this crop-livestock-forest integration system (ICLF).

No expenditure was considered for carbon due to the variation in the costs of monitoring carbon balance and certification, activities necessary to realize the generation of credits.

Expenses with corn harvesting in the spreadsheet represent the entire expense with the crop. As cash flow is annual, all expenses should always be summed into a single piece of information. It was decided to include all expenses of the annual culture as part of the price. For each ton of corn harvested, the average expenditure will reach R$ 1,199. The same methodology was used to represent livestock expenses in this exercise. It was also considered R$ 10,000 per hectare for the price of land and R$ 500 for its lease.

If it were necessary to supply an industry with an expected production of 3,500 tons of oil per year, at least 1,000 hectares should be planted, distributed in 14 plots of land, which can be deployed gradually, over nine years. Each plot would have an area between 70 hectares and 80 hectares.

The Minimum Attractiveness Rate is an interest rate that represents the minimum that an investor desires to earn when making an investment, or the maximum that a person proposes to pay when making a loan. The attractiveness rate was estimated at 5.25%, coinciding with the Selic rate at the time of calculation (August 2021).

Productivity estimates were based on references showing more conservative amounts confirmed by more than one source. The values considered for macaúba prices were also chosen in the same way. In the case of corn and livestock, national averages for extensive livestock farming and conventional corn plantations were used. As for carbon, prices were also the lowest found in the available references.

In the analysis of macaúba biodiesel market potential, different exercises were carried out to estimate a conservative cash flow, yet covering production costs and ensuring a reasonable rate of financial return for producers of the species.

The cash flow considers minimum possible revenues for the unknown crop, and average revenues for known crops, such as corn. The costs are the only ones found in literature, but they are not different from similar cultures expenditure. Therefore, revenues are as low as possible for the proposed model.

Although the operational Internal Rate of Return (IRR) is acceptable, figures also show that such minimum cash flow, as proposed in the exercise, after several simulations, is only able to pay taxes and investments if land price is less than R$ 3,000 per hectare.

[26] (PIMENTEL et al., 2009)

09.

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