MACAÚBA'S WORLD SCENARIO: A BIBLIOMETRIC ANALYSIS

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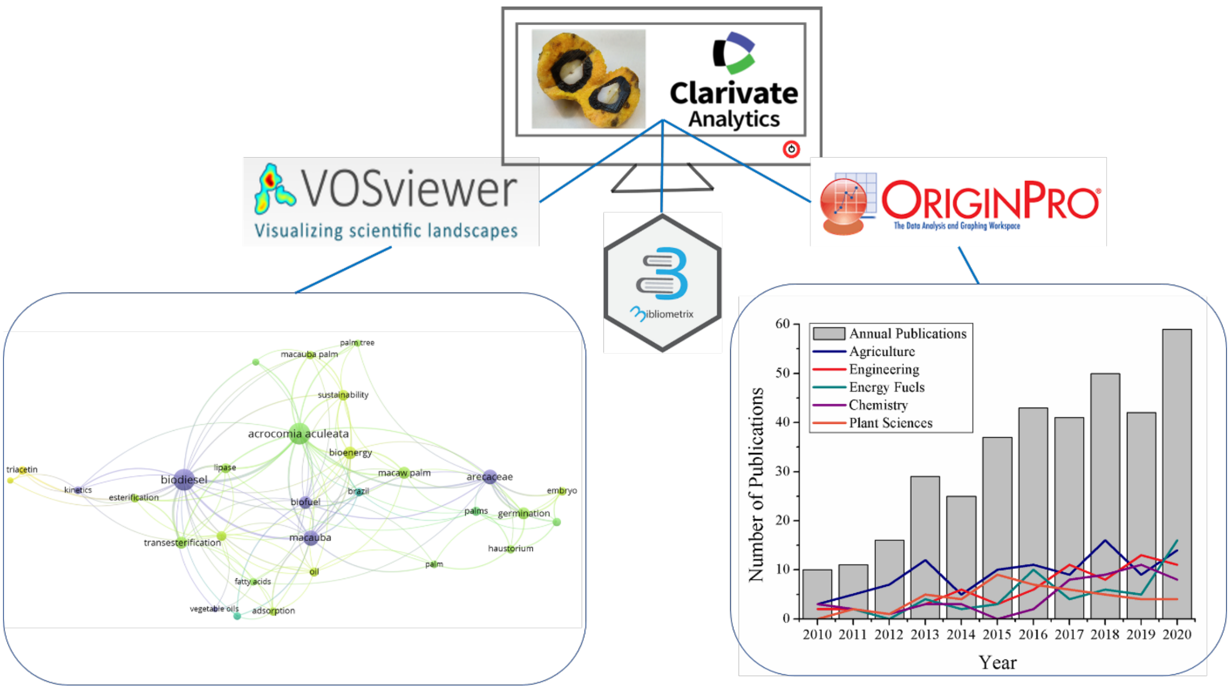
Graphical abstract



ABSTRACT

Macaúba is a tropical palm native in South and Central America, and its fruits present a high-quality oil for biodiesel production. Notwithstanding, *macaúba*'s wastes and by-products are not usually repurposed as energy sources. This study shows a bibliometric analysis to assess *macaúba*'s current applications and to investigate other energy recovery routes for its by-products. All the investigations focused on information about the main research fields related to *macaúba*. The study showed that only 397 articles and reviews were published from 1900 until 2021, and Brazil is the leading publisher. Although oleic and protein *macaúba*'s by-products are applied as animal feed, some conversion routes related to the lignocellulosic contents, present in non-edible parts, were identified thermal conversion, combustion, gasification, pyrolysis, biochemical conversion, fermentation, esterification, and anaerobic digestion. From the agricultural perspective, plant characterization, germination, embryogenesis, and seed development were also found. From the bibliometric study, the different potential applications of *macaúba* for energy, pharmaceutical, and food purposes were listed to support the identification of a knowledge gap on its by-products revaluation.

Keywords: *By-products, Waste, Bioenergy, Systematic Review, Acrocomia aculeata*

DECLARATIONS

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1. INTRODUCTION

Acrocomia aculeata, "*macaúba*", a member of the Arecaceae family, is native to South and Central America [1]. The plant is highly productive, arborescent, and spiny, producing large bunches of fruits [1-4]. The palm is more vigorous infertile soils, occurring mainly in areas with high solar radiation. It can equally adapt to sandy and clayey soils and presents a low water requirement [5]. *Macaúba's* fruits are composed of: tough and fibrous husk (epicarp), yellow and oleic fleshy pulp (mesocarp), and a black tissue (endocarp) containing one or even two white nuts (endosperm) [6,2]. *Macaúba* has an interesting chemical composition, starting from the husks' lignin content is 27.52%, while the values for pulp cake, endocarp, and kernel cake are, respectively, 29.25%, 31.67%, and 32.70% [2]. For the husks, elemental composition, the values of carbon (C), hydrogen (H), and nitrogen (N) are equal to 47.20%, 7.26%, and 0.43%. The content of C, H, and N in the pulp cake are 43.84%, 7.42%, and 0.88%, in the endocarp 48.00%, 6.19%, and 0.56%. Finally, for the kernel cake, the elemental content is 45.00% C, 7.41% H, and 6.35% N [2]. The fruit kernel fatty acid composition is lauric acid (43.6%), oleic acid (25.5%), myristic acid (8.5%), caprylic acid (6.2%), capric acid and palmitic acid (5.3%), linoleic acid (3.3%) and stearic acid (2.4%). The fatty acid content from the mesocarp is oleic acid (53.4%), palmitic acid (18.7%), linoleic acid (17.7%), palmitoleic acid (4.0%), stearic acid (2.8%) and linolenic acid (1.5%) [5]. The oil extracted from the mesocarp is rich in oleic acid. It presents high oxidative stability and operability at low temperatures. At the same time, the oil from the endosperm is rich in short-chain saturated fatty acids, mainly employed for pharmaceutical and cosmetic purposes [1,6]. Both oils present suitable physicochemical properties for biodiesel production, which results from the high presence of lauric acid that facilitates esterification reactions [5]. Additionally, *macaúba* oil extracted from pulp is rich in oleic acid, resulting in biodiesel of good quality containing high monosaturated esters in high concentration [7]. The by-products, husks and endocarp are mainly destined for combustion [8].

Macaúba's species occurs in almost the whole Brazilian territory. It is spread over all five (5) regions of the country - North, Northeast, Midwest, Southeast and South [9]. The main producers are located in *Minas Gerais* state, where an expressive economic importance/potential is observed. [5,10]. Because of *macaúba's* natural occurrence in Brazil and its oil characteristics, a growing biodiesel industry is flourishing, especially in *Minas Gerais* state [11,12]. Cruz et al. (2020) showed dates about *Macaúba's* biodiesel production and report in the composition of biodiesels produced from oilseed fruits 64.50% of carbon and higher heating value (HHV) of *macaúba's* biodiesel is 39.23 MJ.kg-1. Despite the high-quality biodiesel obtained from macaúba's oil, it's an incipient industry that still requires further research [13].

Macaúba's productive chain is primarily extractive, and the fruits are manually picked up from the ground, resulting in a low-quality final product [5,10]. For this reason, several measures were adopted by the Government of Minas Gerais, such as the "*Pro Macaúba's Law*" [14], which encourages the cultivation, extraction, marketing, consumption and processing steps. Brazilian biodiesel can be obtained from several raw materials, like fats and oils from animals, palm (*Elaies* sp.), sunflower (*Heliantusannus*), babassu (*Orbignyaphalerata*), *macaúba* (*Acrocomia aculeata*), *pequi* (*Brasilia caryocar*), soybean (*Glycine max*) and even from sugarcane (*Saccharum officinarum*) [5]. According to ANP (National Petroleum Agency) the main raw material for biodiesel production in Brazil is soybean oil, which reached 4,000,116.40 m^3 in 2019, 67.80% of the total national production. The most recent data available shows the Brazilian soybean biodiesel production in 2020, from January to April, corresponds to 1,367,036.54 m^3, which is 70.58% of the total production period [15]. At the same time, Brazilian soybean biodiesel is predominant. The country exported 83,605,198 tons of soybeans only in 2018, leaving opportunities for other oil crops with great potential for biodiesel production [16].

Considering the high productivity of *macaúba* in terms of oil, the flourishing biodiesel industry presents great potential for further expansion. Even considering a conservative scenario with a low density of 400 plants.ha^{-1}.$year^{-1}$, the oil production would be 2.5-ton oil.ha^{-1}.$year^{-1}$, while in an optimal situation, the yield could reach 5 ton.ha^{-1}.$year^{-1}$ [12]. Additionally, the cultivation of *macaúba* is feasible for small farmers. The cost of commercial crops (US$ 24.64/ton in 2011) was very competitive when compared to other cultures in the same year, like *Jatropha curcas* (jatropha, US$ 47.18/ton), *Ricinus communis L.* (Castor bean, US$ 151.91/ton) and soybean (US$ 79.35/ton) [5]. In 2014 the price of *macaúba* oil in state of Minas Gerais was estimated in R$3.70/L of pulp oil and R$4.00/L of nut oil, which correspond to US$ 0.7/L and US$0.76/L [17]. The National Supply Company (Conab), with the federal government, established the most recent minimal price for Brazilian *macaúba* in 2019 as 0.665 R$/kg of fruit or 0.13 US$/kg of fruit [18]. Nowadays, *macaúba* is only cultivated at a small scale combined with other land uses, then the data to assess the biomass production costs are highly uncertain [19,20]. For the next years, a recent research was conducted to evaluate the techno-economic potential of biojet fuel production in Brazil, considering multiple feedstocks, including *macaúba* [20]. An increase in biomass potentials is observed, and biomass production costs generally decrease toward 2030, assuming values on average 4% lower than in 2015. The same study indicates *macaúba* is able to grow over suitable areas in the Cerrado (Savannah), although if no major on-farm improvement is introduced, the production costs can be higher in the coming years [20]. Finally, it is noteworthy to highlight that the oil demands are so high that virtually all of the bio-oil produced worldwide is absorbed by the market, placing *macaúba* and its biodiesel in good prospects [5]. In 2020 the oil demand presented a decay because of the pandemic, with historic turbulence in energy markets. In December 2019, the global oil demand presented the strongest annual growth in a year, reaching 900 kb/d (kilo barrel per day) [21]. The preliminary forecast to total world oil crop production for 2020/21 is 613.3 million tons [22]. For biodiesel production, there are some advantages of *macaúba* over other crops: (i) high oil productivity (that may reach 5,000 kg of oil per $ha^{-1}.year^{-1}$) in a relatively easy extraction process, (ii) plant adaptation to different soil types, (iii) contribution to degraded areas recovery (from mixing *macaúba's* cultivation with intercrop and agroforestry systems), (iv) high CO_2 absorption capacity (10.00 $Mg.ha^{-1}$), almost 3-fold higher than soybean (3.52 $Mg.ha^{-1}$), while 3-fold lower than palm oil (29.30 $Mg.ha^{-1}$), (v) profitability for farmers and rising market prices (in 2009 the cost of *in natura macaúba* was around USD $25.ton^{-1}$, and in 2011 it increased by 30% to USD 32), (vi) job generation, and (vii) a market in expansion presenting a growth of 20.9% from 2010 to 2015 [23,19,5,12,3,24].

In 2003, the Brazilian government adopted two strategies to reduce pollutants' emissions and to boost the production of fuels from renewable biomass, the Inter-ministerial Executive Committee on Biodiesel (CEIB, from Portuguese) and the Management Group (GG). Further, in 2004, a new state policy, the National Program of Biodiesel Production and Use (PNPB, from Portuguese), encouraged a criterial mixture of biodiesel in diesel. From 2005 to 2007, the B2 blend was commercialized as a mixture of 2% biodiesel and 98% diesel marketing. Since 2008, biodiesel's fixed additions in the marketed diesel became mandatory, and, more recently, in March 2020, the B12 proportion was regulated [15,25].

Another Brazilian Government state policy called "RenovaBio" was established to accomplish the Paris Agreement's national commitments in 2016 [26]. RenovaBio aims to recognize all kinds of biofuels and their use to assure the country's energy security while contributing to the fuel sector decarbonization. Among these biofuels, special attention is given to ethanol, second-generation ethanol, biodiesel, biogas and biomass [15].

An attractive development strategy for Brazil, an agro producer country, is the rational use of renewable energy from biomass. The use of residual biomass as a source of energy and materials on a sustainable basis is essential to achieve higher energy use rates and maintain or expand the country's energy security. Obtaining new products that favor the development of a ‘circular economy’, recycling, reusing and adding value to materials at the end of their consumption cycles requires advances in the use of existing technologies and innovation. A 'circular economy' minimizes the generation of waste and recovers by-products energy while closing industrial cycles [27,28].

Despite several research types on *macaúba's* characterization, cultivation and potential biodiesel production were found in the scientific literature, no bibliometric studies were identified. The bibliometric analysis involves mathematical models and statistical methods to assess a particular research field's literature information. It is based on the structure, relationship, and variation law of the collected literature data and allows setting the knowledge advances in the target field. A peculiar utility of the bibliometric analysis is the prediction of developing hotspots and new or ascending research fields to collect information about knowledge gaps in a specific area [29].

This study presents a bibliometric analysis of *macaúba's* potential applications to investigate further alternatives for fruit processing and recovering energy through by-products. Finally, this study aimed to identify possible knowledge gaps on macaúba's by-products energy recovery to support future research.

2. MATERIALS AND METHODS

2.1. Data Collection

The bibliometric study followed six steps (**Figure 1**): (I) topic definition to describe, in detail, the current state of *macaúba's* research; (II) selection of databases and platforms privileging those that offer the necessary analytical tools for bibliometric calculations; (III) selection of keywords to prepare the literature data collection; (IV) bibliographic search; (V) data exportation; and (VI) data analysis.

Scientific output data were obtained from the core collection of Science Citation Index Expanded (SCI-E) – Clarivate Analytics' ISI – Web of Science© (WoS - https://webofknowledge.com/) to "Topic" (title, abstract, authors' keywords and Keywords Plus) on January, 14th 2021. The type of search applied was "basic search" and the types of documents were filtered to "article" and "review" to obtain reliable and accurate details on the Topic. A total of 397 publications were gathered, using "*macaúba*" or "macauba" or "macaw palm" or "*Acrocomia aculeata*" as the search query, for the period from 1900 to 2021.

To analyze the patents related to *macaúba* scientific data were obtained from all databases of SCI-E– Clarivate Analytics' ISI – WoS© to "Topic" (title, abstract, authors' keywords and Keywords Plus) on January, 18th 2021. The type of search applied was "basic search" and the types of documents were filtered to "patent". A total of 14 patents were gathered, using "*macaúba*" or "macauba" or "macaw palm" or "*Acrocomia aculeata*" as the search query, for the period from 1900 to 2021.

Figure 1

2.2. Bibliometric Analysis

The "Bibliometrix" package (R language) was used to obtain a three-field plot identifying the countries and how they are related to the most common authors' keywords and sources in *macaúba* field [30]. Besides, the obtained dataset was applied to VOSviewer software to build clusters containing information related to authors, coauthors and the most common authors' keywords (VOSVIEWER, 2019). Finally, Origin® was applied to analyze the absolute number of publications per year in the last decade and the 5 most frequent research areas. All the data for the bibliometric analysis was extracted from WoS.

The VOSviewer software starts the maps building from a co-occurrence matrix. A similarity matrix is calculated to correct the differences in the total number of item occurrences or co-occurrences in the first step. In the next step, a two-dimensional map is obtained by applying the mapping technique to the similarity matrix, and issues with high similarity are located close to each other. In contrast, items that have low similarity are located far from each other. Finally, the map is translated, rotated and reflected. This way, the same co-occurrence matrix should always yield the same map [31]. For the final maps, the distance between two items reflects the strength of the relation between them [32]. On the images, the thicker the lines that connect the items, the higher is the strength linking them, and generally, the smaller the distance between items, the more related they are [31].

The VOSviewer software running set was defined as the "full counting" method. This choice makes it possible to account for how many times an author or coauthor, or keyword appeared in the different documents. Publications with more than 15 authors were not included, and the minimum number of documents per author was set to 5. The authors' names were reduced to their initials. From the initial 1387 authors identified in the original search, 30 met the established threshold and, some of them were not connected. In the study of authors' keywords, the initial number was 1076, and 35 completed the limits. Finally, only the 30 words with the highest total link strength were selected.

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis

In the past 10 years, 363 documents including "*macaúba*", or "macauba", or "macaw palm", or "*Acrocomia aculeata*" were found, corresponding to 91.44% of all WoS publications. **Figure 2** presents the number of publications from 2010 until January 14th, 2021. The lines represent the number of publications for the top 5 research fields.

The most expressive research field is Agriculture (101 publications), followed by Engineering (66), Energy fuels (52), Chemistry (50) and Plant Sciences (47), anyway, the number of publications per area does not follow a trend. It is possible to notice an increasing number of documents, with the highest level in 2020 (59) and a slight decay in 2019 (42). Yet, in recent years, a growing interest in *macaúba* for cleaner and renewable energy production allows inferring that more studies in plant and seed development and processing follow the same energy research trend, probably to support higher yields for energy purposes.

Figure 2

Table 1 presents the most discussed issues over the years, also including the main research fields. One document related to *Salto Macaúba's* farm was present only for a coincidence of the term "*macaúba*" [33]. No other miscommunications like this were noted. From 2010, studies related to energy became evident, especially for biodiesel production [34,35] and the use of by-products for coal [36]. After 2014 a higher number of research on biofuels is present, which can correlate to the increasing interest in cleaner energy sources and sustainability. Even though the main destination of *macaúba* by-products is for animal feed, research on energy obtention through pyrolysis and coal production from non-edible parts is in evidence. In the same period, it is possible to observe an increase in by-products valorization as biochar for the adsorption of different chemicals. Still, this theme appeared for the first time in 2012 in the adsorption of dyes [37]. For the year 2020 (**Table 1**) the research area of Energy Fuels was the most expressive, with 16 accepted publications, corresponding to 27.12% of the total (59 papers). In second place, appeared "Agriculture" with 14 publications (23.73%), followed by Engineering with 11 articles (18.64%).

Table 1

3.2. Bibliometric Analysis of Countries

Figure 3 presents a three-field plot (Sankey diagram) with the top 10 countries, the 10 most frequent authors' keywords, and the top 10 journals [30,38]. Brazil is the principal knowledge producer, responsible for 87.41% of the publications. This result is probably due to *macaúba's* large occurrence in Brazil. The second country is Spain (5.54% of the publications), followed by the United States of America (5.04%). Among the journals, Industrial Crops and Products (impact factor 4.244) is the most frequent publisher (27 documents), followed by Fuel (impact factor 5.578 and 12 documents), *Ciencia Rural* (impact factor 0.0644), and Renewable Energy (impact factor 6.274 and 9 documents each).

Figure 3.

Brazil is also the leader in the number of publications related to all the top 10 authors' keywords (**Figure 3**). The most used keyword is the scientific crop name (*Acrocomia aculeata*), followed by "biodiesel" and "macauba". Other keywords that provide insightful information on the main research areas are biofuel, germination and lipase. The authors' most frequent keyword is *A. aculeata*, which is necessary to all the scientific community to recognize the species studied since the common name given to "*macaúba*" can vary in different countries and even in Brazilian states. The words "biodiesel", "biofuel" and "lipase" appeared as a consequence of the great potential in the use of *macaúba* oils to produce biodiesel, bio-jet fuel and biokerosene [39-41].

Table 2 presents the three most productive countries, the research fields, the most common authors' partnership, and their respective countries. It is possible to notice the collaboration between Brazil, Spain and the United States of America, which represent 97.99% of the publications. This partnership is important to understand and evaluate the worldwide importance of *macaúba* and its applications in countries other than Brazil. The first publication associated with *macaúba* is from 1991, and it was developed in Brazil. The first document from the United States of America dates from 2004, while in Spain, the first study occurred only in 2014.

Brazil occupies the top position in the ranking of the most productive countries with the Agriculture research field as the most frequent topic. Among the Brazilian publications, the most cited document presents 118 citations. With the increases in biodiesel production, an excess of crude glycerol was occasioned, so the most cited article presents a review and analysis of patents about glycerol use, showing the extraordinary efforts to add value to glycerol from biodiesel production [42]. This article is not directly related to the application of *macaúba* itself, but it includes the plant as one of the feedstocks used for biodiesel production. Since biodiesel production is one of the most discussed topics, and glycerol surplus consists of a major bottleneck in the biodiesel production chain, it is reasonable that this work would have more citations.

The most discussed research field in Spain is Plant Sciences (**Table 2**). The most cited paper from Spain presents 79 citations. It reports the use of *macaúba's* endocarp to activated carbon production and the biochar characterization, aiming to remove Rhodamine B from aqueous solutions [43]. Rhodamine B is an example of an industrial pollutant dye with harmful properties. Synthetic dyes produce many toxic, carcinogenic, mutagenic, and bio-accumulative compounds that contaminate the wastewaters, making it necessary to use non-conventional wastewater purification treatments [44,45]. In this document, the authors describe the production, characterization and use of activated charcoals obtained from three lignocellulosic waste materials, including *macaúba* endocarp, for the adsorption of contaminants in wastewaters. The contamination of water and wastewater with dyes, heavy metals and other chemicals consists of a current environmental problem, explaining the study's importance and several citations. The authorship includes some of the most important authors from Spain (refer to **Table 2**).

Among the publications from the United States of America, the most impacting research field is Engineering (**Table 2**). The most cited article presents 39 citations. It is focused on seed dormancy presented by different *macaúba* palms species [46]. Studies on seed dormancy, germination, embryogenesis and other agricultural/morphological traits on *macaúba's* development are indispensable to establish plantations for commercial purposes. This research area is one of the most prevailing, and the authors are not listed among the most productive from this country.

3.3. Most Productive Authors and Coauthors

The network of the 30 most expressive and most productive authors in the field is presented in **Figure 4**. The total number of authors collaborating in the 397 publications found on the WoS core collection is 1387. The most prominent circles indicate the higher number of documents published by each author. The lines represent the links between them, and the size of the line is proportional to its strength. It is possible to observe four different clusters not closely related to each other when the number of authors selected was 30. Simultaneously, the most extensive set of connections consisted of 10 items, with other authors isolated from these clusters.

Among the authors, Motoike, S.Y. has the highest number of documents, totalizing 27 publications. Considering both the number of publications and the number of citations, he is the most cited author globally, 405 citations, followed by Ribeiro, L.D. with 23 publications and 310 citations Kuki, K.N. with 13 publications and 179 citations.

The most cited article authored by Motoike, S.Y. (66 citations), published in 2010, deals with anatomy, histochemistry, and structure of *macaúba's* seed and its embryos using light and transmission electron microscopy, aiming to understand the seed post-harvest behavior and the establishment of plants from somatic embryos [47]. The attention given to *macaúba* has been growing recently, and most part of publications are from the past ten years. Studies in this area are important due to the scarce information about the seed structure and its technological characteristics, resulting from the novelty of the topic under debate. The second most cited article, published in 2013, presented 65 citations. Other publications were related to harvest, plant and fruit characteristics and development, seed production and biofuel [48-53,2,54-66].

The most cited document from Ribeiro L. M., published in 2011, 45 citations, exposed that dormancy (when the seed has favorable conditions but does not germinate) is not completely understood for most species of Arecaceae. Considering this, they have tested methods to find the best treatments to stimulate germination [67]. In the second most cited article, authored by Ribeiro, L.M., 43 citations, published in 2012, the collaborators examined the morphology and anatomy of *macaúba's* embryos and seedlings *in vitro* germination. Ribeiro's production was related to *macaúba's* seed, structure, germination, pretreatments, storage conditions and reserve mobilization [68-83]. Considering the potential use of *macaúba* for biodiesel, it will be necessary to accomplish commercial scale plantations, which are currently limited by difficulties related to the plant propagation. The fact happens mainly because of seed dormancy and slow germination, which occurs only in low percentages. Considering the above discussed, studies conducted by Ribeiro L. M. are indispensable for the entry of *macaúba* in the market.

The third most productive author is Kuki, K. N., with 13 publications, most of them (84.62%) done with Motoike, S. Y. as a co-author or as the group's leader. The most cited work, 65 citations, published in 2013, was related to ecophysiological aspects of *macaúba* under semi-arid field conditions, like foliar content, gas exchange parameters, diel variation, light intensity and position within the tree canopy and rachis [84]. Scarce data is available about the ecophysiology of *macaúba,* and often it refers to environmental conditions different from those found in the semi-arid region. The main importance of this study was to increase the knowledge of the species under semi-arid conditions.

Other publications of Kuki, K. N. evaluated the potential of *macaúba* as feedstock for solid biofuel; air drying to maintain its quality for biodiesel production; molecular characterization and population structure; patterns of fruit development; changes in morphology and storage compounds. Besides, methods to test and to predict the biomass of *macaúba's* fruit and genetic composition to support conservation programs and molecular biology were also found [53,85,2,56-58,60,86].

Figure 4.

3.4 Patents

Table 3 presents the 14 patents related to *macaúba*. The eldest document found during the research is from 2013, proving studies with this fruit are recent. Even with the growing interest in using *macaúba* for biofuel production, most of the patents are not associated with this research area. Only two patents connected to biodiesel were found [87,88]. One patent stablishes the use of a broth obtained after grinding bark, leaves and fruit of *macaúba* and other palms to obtain a nutritive solution containing macronutrients for plant development, namely nitrogen (N), phosphorus (P) and potassium (K). This use of *macaúba* is of great interest to produce organic vegetables, avoiding industrial chemicals. Two patents focus on using a mixture of vegetable oils [89] and only *macaúba* oil [90] as collectors in minerals' flotation. These methods enable the separation of minerals more efficiently and sustainably. In the same line of using *macaúba* for separating materials, one patent establishes a process for obtaining biochar from the fruit endocarp [91]. In contrast to other studies using *macaúba* for biochar, this patent offers a final product suitable for gaseous and liquid media. Consequently, it can be used for retaining particles present in the air.

One interesting patent developed in Brazil establishes a method for preparing nutrient tablets using the *macaúba* pulp [92]. This application is different from those reported in articles about using *macaúba* in the Food Industry [93-95], focusing on the use of the oil from the mesocarp and endosperm of the fruit. Another document presents the use of milled *macaúba* husks to produce and organic abrasive used for sandblasting with applications in automotive, aviation, subway, nautical and textile industries, presenting the advantage of easy disposal [96]. Among the documents, a method for germinating palms was shown [97]. Given the great importance of finding the best way to implant a commercial scale plantation of *macaúba*, and considering the dormancy of *A. aculeata*, germination methods are indispensable, was well as for identifying and separating *A. aculeata* and other species of *Acrocomia* [98]. In animal feed, only one patent was found, which consists of the production of a nutritional bulk using the pulp of *macaúba* [99]. Finally, two patents are related to uses in the pharmaceutical industry. The first present active ingredients for pharmaceutical composition, nutritional supplements and cosmetics for treating and preventing acute and chronic inflammation, increased oxidative stress, osteoarthritis, benign prostate hyperplasia and prostatitis [100]. The second one is a soap formulation from the *macaúba* pulp oil, and the use of the product is associated with skin texture improvement [101]. The diversity of areas in which intellectual protection was established proves the versatility and high applicability of *macaúba* for different purposes.

Table 3

3.5. Most Frequent Authors' Keywords

Figure 5 presents 5 clusters for the 30 most frequent authors' keywords that appeared at least five times for the 397 selected documents. Among the 1144 authors' keywords, the most frequent, "*Acrocomia aculeata*", appeared 73 times, followed by "biodiesel" and "macauba" (53 and 36 times, respectively).

Cluster 1, the biggest (8 items), is formed by the words "biofuel", "macauba", "acrocomia aculeate", "pyrolysis", "fatty acids", "adsorption", "vegetable oils" and "oil", forming a group related to oil extraction and its application to biofuel production. The word "adsorption" present in cluster 1 brings to evidence a research area of great interest: the use of biochar from *macaúba* in the adsorption of water contaminants and even for the treatment of emerging contaminants [102-109,37]. In the cluster 2, "Arecaceae", "palms", "germination", "palm", "hastorium", "embryo" and "operculum" words are related to embryogenesis and seed studies. The cluster 3 is formed by the words "biodiesel", "esterification", "kinetics", "lipase", "methyl acetate", "transesterification" and "triacetin". This cluster is directly linked to Energy Fuels and Environmental Sciences area since "biodiesel" is intimately associated with renewable energy sources. In cluster 4 the most frequent authors' keyword "*Acrocomia aculeata*" was found, additionally, this cluster presents the words "genetic diversity", "macauba palm", "palm tree" and "sustainability". And, finally, cluster 5 is established by the words "bioenergy", "brazil" and "macaw palm".

The timeline bar in **Figure 5** makes it possible to follow the main explored issues from 2000 to 2020. In the early 2000's, keywords suggest the biofuel research area. In 2010, a transition to energy recovery is observed, following studies on adsorption and transesterification. Finally, in 2015 it is possible to follow a trend on germination and embryo studies, changing to bioenergy, biofuel and sustainability fields in 2020.

Figure 5.

The current trend of using renewable materials to obtain cleaner energy is noticeable by the use of terms "bioenergy", "methyl acetate" and "triacetin" in the last years. During the processing, the mesocarp is removed and the oil is extracted through pressure, generating a protein-rich cake that can be used for bioethanol production [110,8]. The oils extracted from the mesocarp and endosperm are suitable for biodiesel production [111], for uses in chemical and food industries [93-95], and applications in the cosmetics and pharmaceutical industry [112]. From the endocarp, a solid biofuel (biochar) can be obtained for thermal energy generation [2,8] and also used as biosorbent, with possibilities for environmental purposes such as water/wastewater treatment/remediation [102-109,37]. The use of endocarp by-products as solid fuel has been studied to reduce the dependence on non-renewable energy sources, with particular attention given to the endocarp and the epicarp [113]. In contrast, the application as biosorbent is of substantial importance for removing hazardous pollutants from water/wastewater, favoring the environment [43]. However, *macaúba's* by-products are not used for oil extraction and could be converted into energy (for instance, biogas) or animal feed (refer to **Figure 6)**.

Figure 6.

Although thermal energy from biomass combustion to produce steam is the main energy recovery route for *macaúba's* by-products, other technologies are possible. Biomass gasification produces gaseous fuels like hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2) and other gases that can be applied for heat, electricity and/or fuel. Pyrolysis generates a rich liquid hydrocarbon, biochar (solid carbon residues) and fuel gases. Esters and ethanol (C_2H_5OH) can be produced via esterification and fermentation, while anaerobic digestion produces biogas (rich in methane and carbon dioxide).

Anaerobic digestion is worldwide applied to treat organic wastes, and the biogas can be used up in manifold different ways, such as electric and thermal energy generation, and, when converted into biomethane, it is used as a vehicular fuel or can be injected into the natural gas grid [114-120]. In general, it is possible to observe that the research on *macaúba's* by-products valorization was mainly developed to animal feed, biochar production and some paths for energy obtaining. No scientific information was identified on anaerobic digestion.

4. CONCLUSIONS

The bibliometric analysis indicated Brazil as the most productive country, contributing with 87% of the publishing on *macaúba*. It was also found that the publications are not focused on a specific research area. Even though it was possible to recognize the prominence of the following areas: agriculture, engineering, energy fuels, Chemistry and plant sciences. Nevertheless, a strong collaboration involving Brazil, Spain and the United States of America was verified, which indicates a foreign interest in *macaúba*. No documents addressing the use of *macaúba's* by-products for biogas production, a promising energy source and environmentally friendly destination to the non-edible biomass, were identified. This knowledge gap indicates the possibility of energy recovery by a well-established technology, worldwide adopted for other agroindustrial by-products. Along with the research on *macaúba's* biodiesel production, other bioenergy sources could be employed to by-products energy recovery to leverage a greener development for this incipient industry. For the flourishing Brazilian *macaúba's* economy, and daring bioenergy and decarbonization state policies, new energy sources are especially attractive to establishing clean development mechanisms intimately associated with regional and world decarbonization targets.

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192. Soccol CR, Belletini MB, Dos Santos JD, Vitola FMD, Fiorda FA, Pedroni Medeiros AB (2015) Nutrient solution used for cultivation of commercial vegetable, fruits, flowers and microorganisms, comprises bark, leaves and fruit of palmeira such as Euterpe oleraceae, Euterpe edulis, Bactris gasipaes and Archontophoenix alexandrae. BR102014008818-A2,

193. Sales Carvalho V, Monteiro Ribeiro L, Pereira De Oliveira G, Mercadante Simoes MO (2015) Flexible extractor device for use during removal of seeds of trees i.e. Acrocomia aculeata, has cylindrical tube and cable provided with protection part, and sharp blades formed with aperture and flow opening and sealed with plastic. BR102013031600-A2,

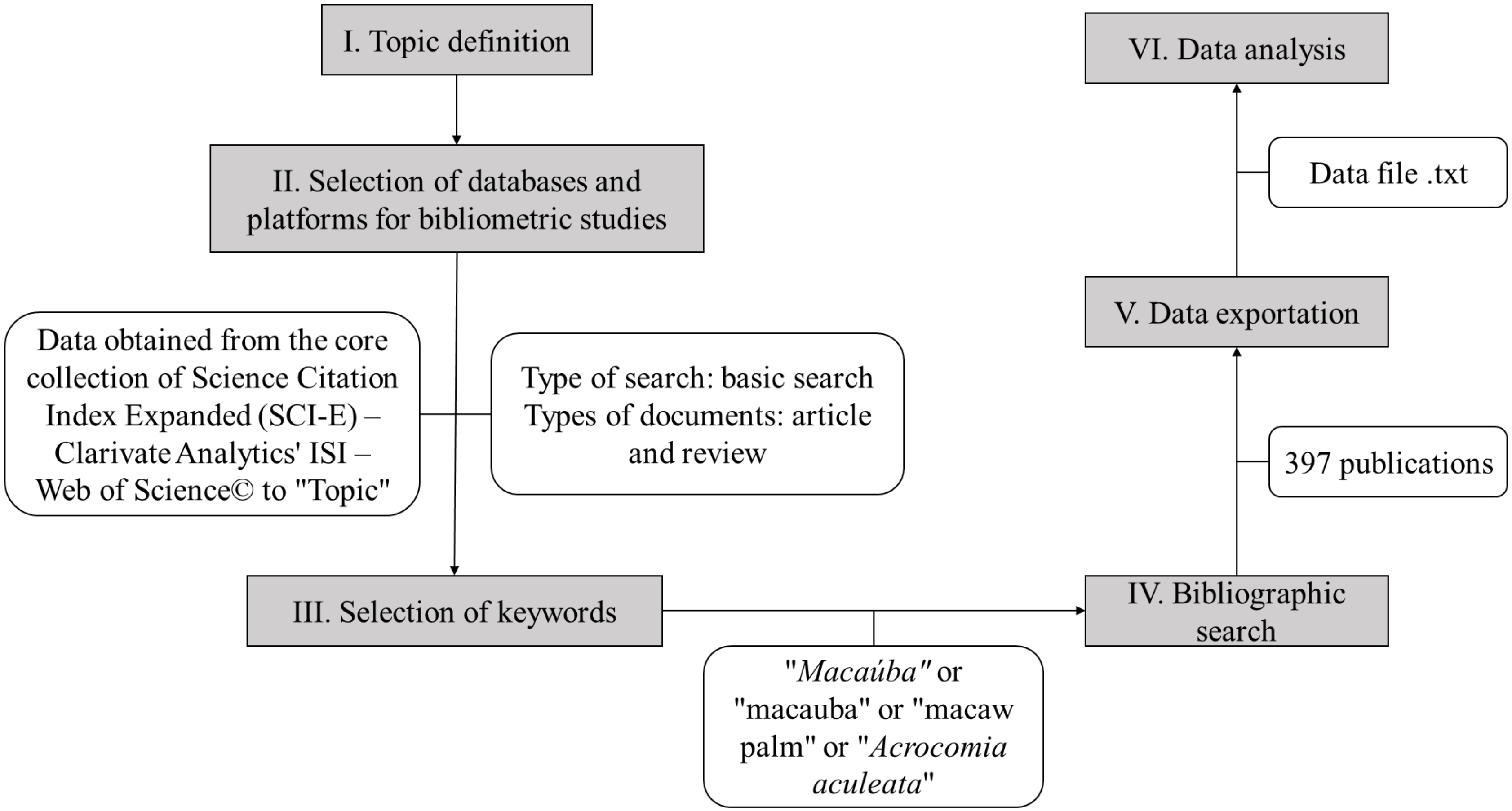
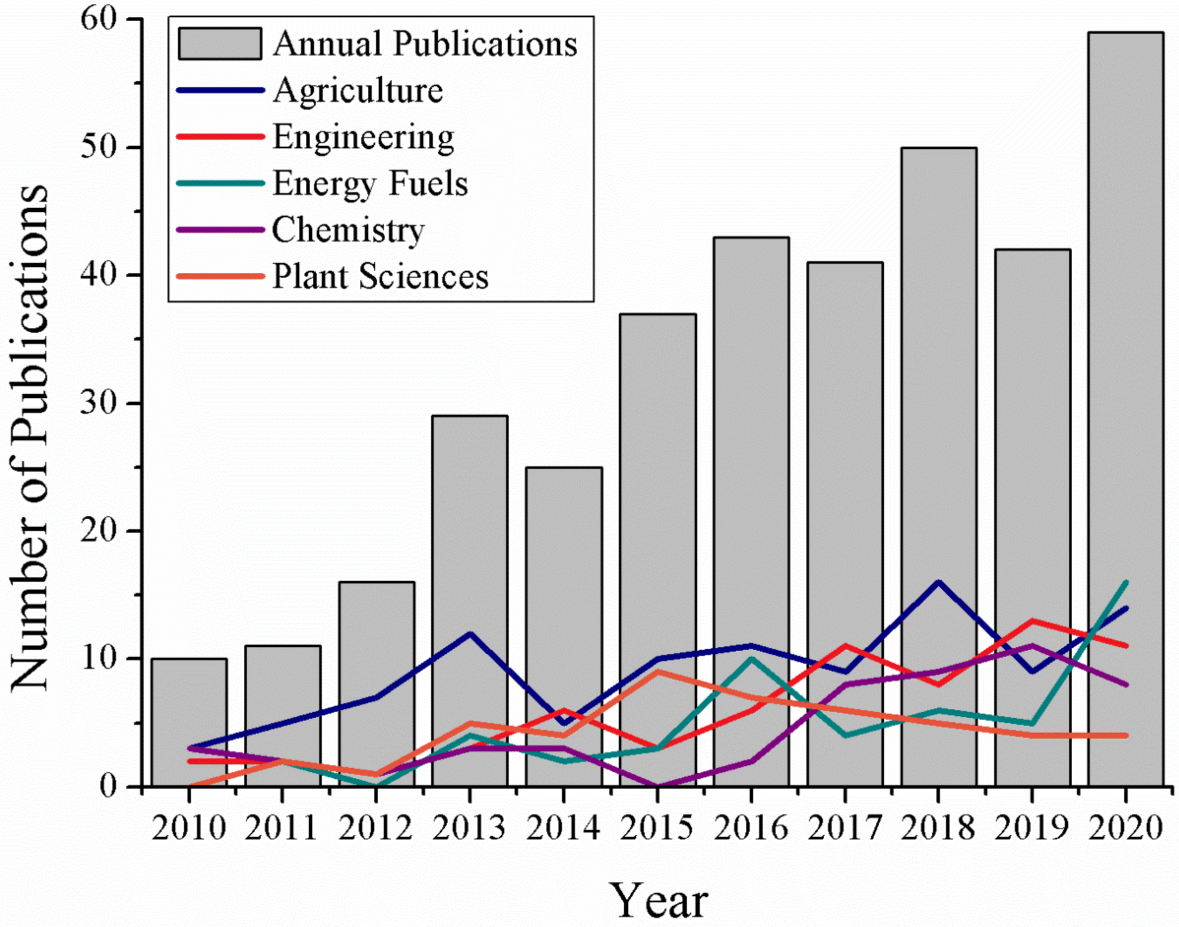


Figure 1. The six steps to produce the bibliometric study.



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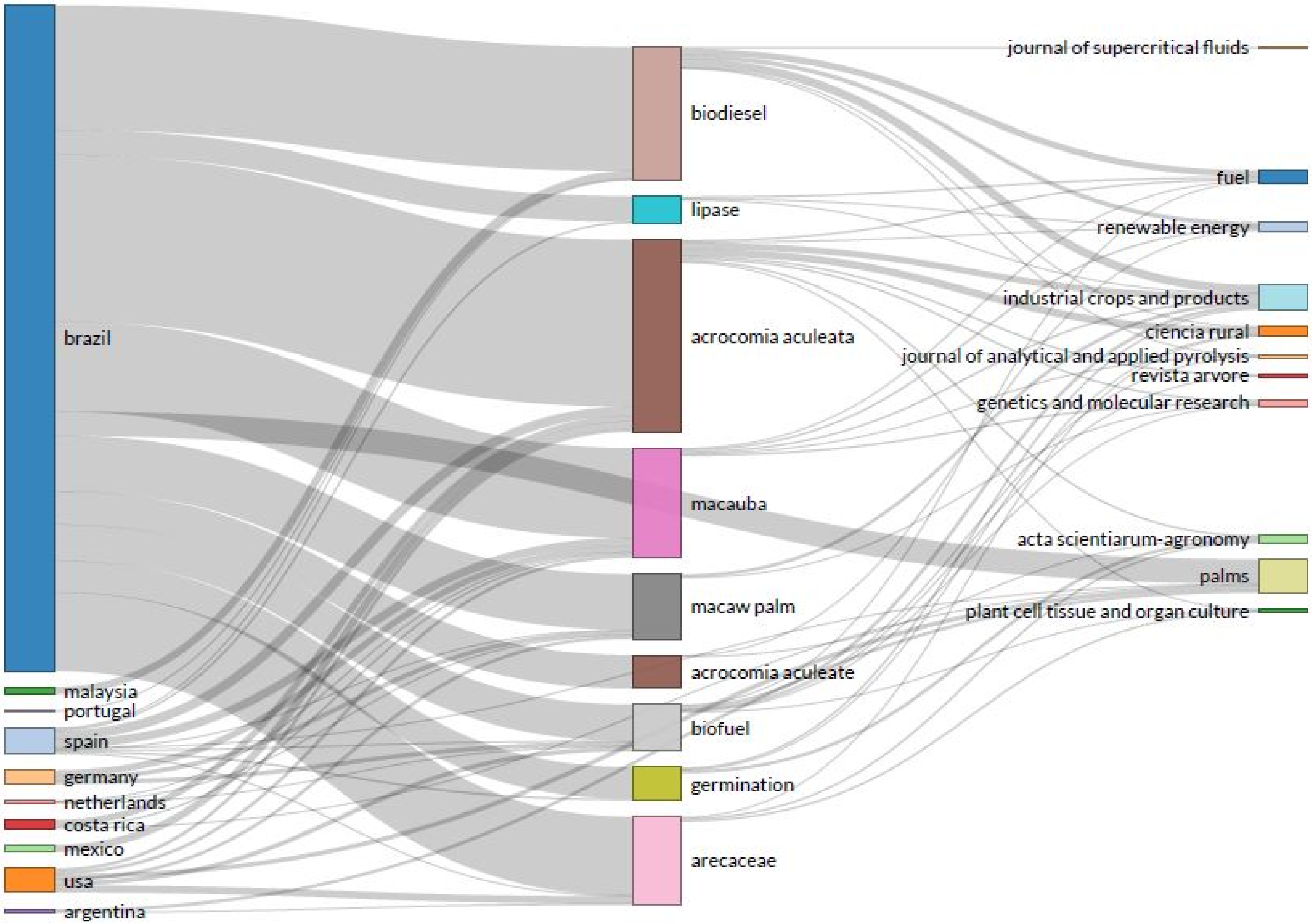
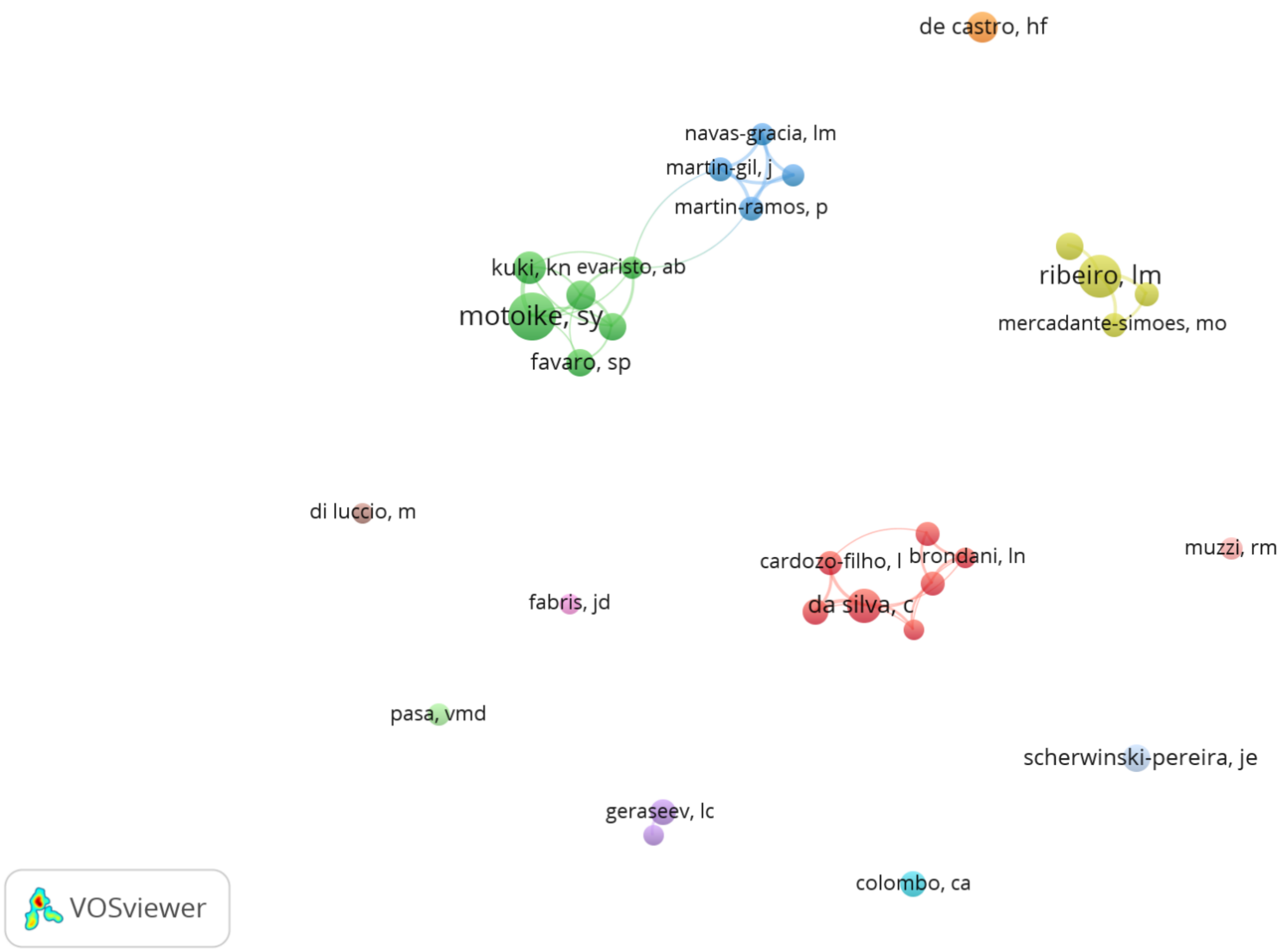
1062 **Figure 2.** The absolute number of publications (bars) and the number of publications in the most frequent research areas per year of publication for the last 10 years.



1064 **Figure 3.** The three-field plot of *macaúba's* research relating the main countries, authors' keywords and journals.



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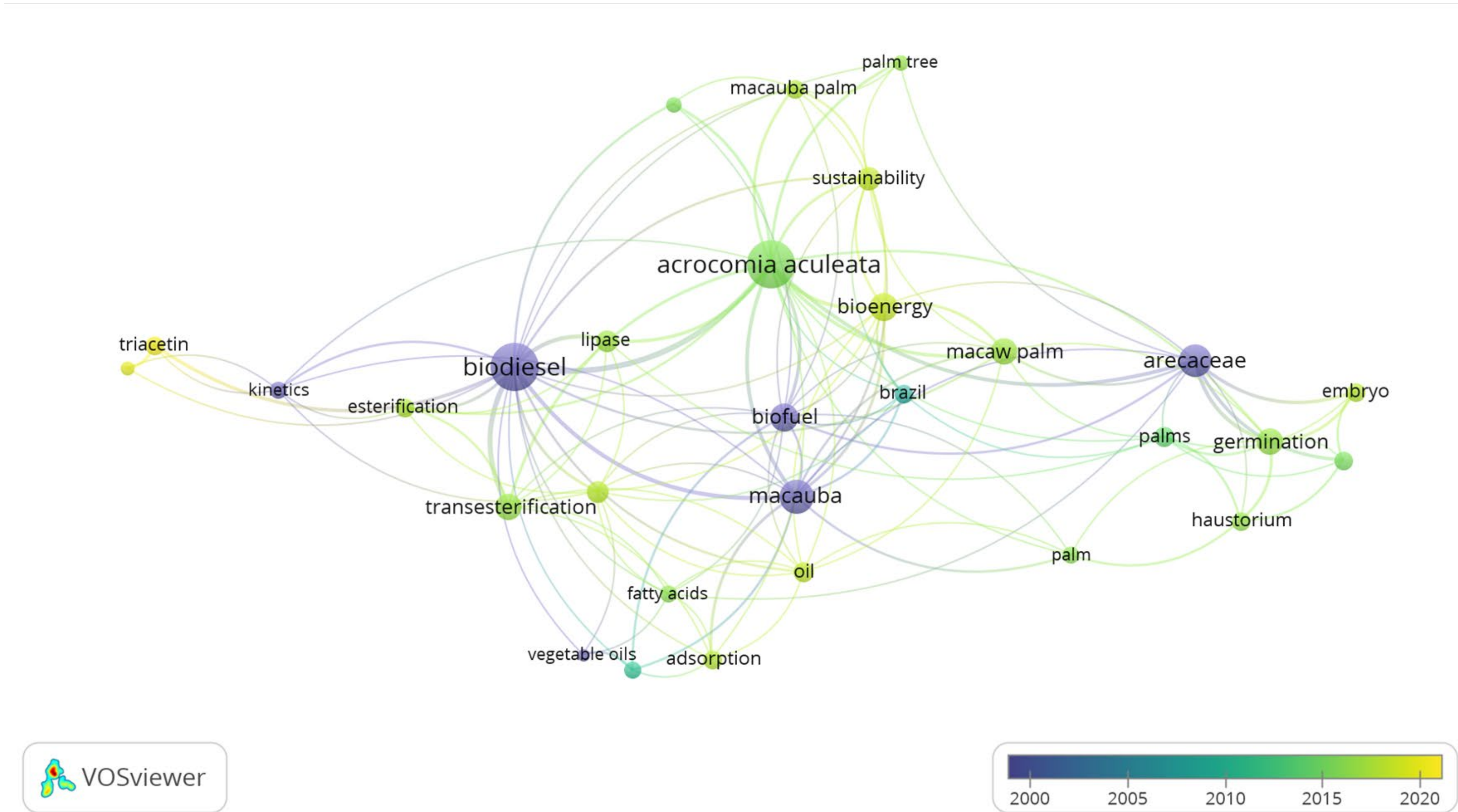
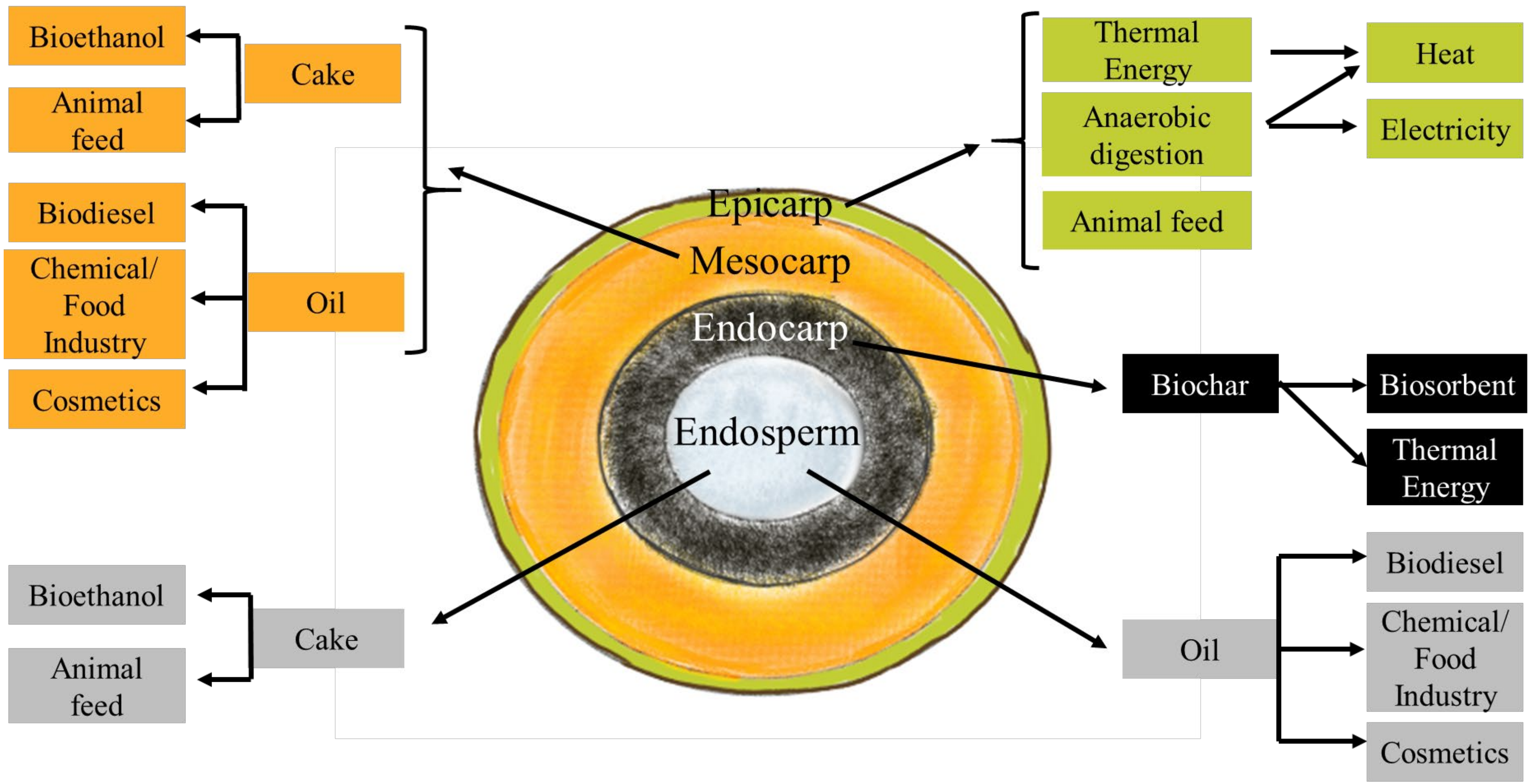
1066 **Figure 4.** The 30 most expressive and most productive authors' network.



keyword	Occurrences
Acrocomia aculeata	73
Biodiesel	53
Macauba	36
Arecaceae	30
Macaw palm	19
Biofuel	16
Germination, palms	13
Acrocomia acualeate	12
Transesterification, lipase	11
Bioenergy	10
Pyrolysis	9
Macauba palm, triacetin, palm tree	8
Palm, vegetable oils	7
Sustainability, haustorium, adsorption, brazil, fatty acids, methyl acetate	6
Oil, embryo, esterification, kinetics, operculum, genetic diversity	5

Figure 5. The 30 most employed author keywords of 397 publications and the respective number of occurrences.



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1070 **Figure 6.** Representation of *macaúba's* fruit and the main products and co-products formed in the productive chain and its applications.

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Table 1. Year of publication, main research fields, issues discussed and number of documents.

Year	Research field	Issue	Number of Documents	References
2010	Agriculture (30%), Chemistry (30%)	Microwave activation of enzymatic catalysts; catalysts using Cadmium compounds; liquid-liquid equilibrium for biodiesel production; use of *macaúba's* waste for coal production; use of *macaúba's* oil combined with cassava starch in thermoplastic biofilms; the bacteria characterization in an alcoholic beverage made from *macaúba's* sap; studies on embryogenesis, germination, anatomy, histochemistry of *macaúba's* structures	10	[35,34,121,36,122,123,47,74,124].
2011 to 2012	Agriculture (30.73%*)	Use of *macaúba's* co-products as animal feed; plant characterization; germination, embryo and seeds development; use of *macaúba* cake as adsorbent for the removal of Methylene Blue and Congo Red;	12	[23,125-128,47,74,73,67,70,129,130,37].
2013	Agriculture (41,38%)	Production of biodiesel and ethanol from *macaúba*; seedling studies	11	[131-139,69,72].
2014	Engineering (24%)	Production of biodiesel; *macaúba* use as animal feed; germination and seed development	10	[140-142,46,143-148].
2014 to 2018	Agriculture (25.31%*), Engineering (17.78%*)	Seed germination; embryogenesis; plant medical properties; biofuel production; harvest and post-harvest treatments; oil extraction; animal feed; emerging contaminants removal using activated carbon from residual *macaúba* biomass; application of the *macaúba's* endocarp for Ni (II) biosorption optimization; biochar for adsorption of fatty acid methyl esters; plant and genotype characterization	18	[149-152,68,5,153,154,85,2,54,155-158,104,105,107-109].
2019	Engineering (30.95%)	Methods to improve esterification and transesterification reactions; aviation biofuels production; botanical information of *macaúba*; productivity tests; genetic parameters for plants selection; embryogenesis; post-harvest treatments to higher/better oil production; *macaúba's* medicinal purposes; sensory characteristics; antibiotic, cytotoxic and antioxidant activities of the oil extracted from the pulp; oil extraction methods and properties; *macaúba* as animal feed; use of biochar for uranium adsorption from aqueous solutions; influence and role of the different biomass components during pyrolysis	21	[159-175,102,176,106].
2020	Energy Fuels (27.12%)	Study of ultrasonic-mediated in situ transesterification for biodiesel; production of fatty acid methyl esters production through interesterification reaction; evaluation of	21	[103,177-180,20,181,182,7,183,39,184-191]

	calcium oxide as catalyst at different calcination temperatures for chemical interesterification of soybean oil; synthesis of renewable heterogenous acid catalyst for glycerol-free biodiesel production; using *macaúba* for biojet fuel and light biodiesel production; investigation of the presence of ethyl esters in transesterified *macaúba* and *pequi* oils; obtaining ethyl esters from *macaúba* pulp crude oil; processing of *macaúba* seed cake using slow pyrolysis to obtain bio-oil; fungal biocatalyst capable of efficiently hydrolyzing *macaúba* oil	

* Average value based on percentages of the respective years

Table 2. Top countries with the highest number of publications, research fields, the most productive authors and partnerships among different countries.

Country	Research Fields	Authors	Partnerships
Brazil	Agriculture, Engineering, Chemistry, Energy Fuels, Plant Sciences, Food Science Technology, Biotechnology Applied Microbiology, Science Technology Other Topics, Forestry and Biochemist Molecular Biology.	Motoike, S.Y., Ribeiro, L. M., Da Silva C, Kuki, K.N., De Castro HF, Pimentel LD, Grossi JAS, Colombo CA, Garcia, Q.S. and Geraseev LC, Guilhen SN, Nelson DL	Spain, the United States of America, Colombia, Portugal, England, Germany, Ethiopia, Ireland and the Netherlands
Spain	Plant Sciences, Agriculture, Biotechnology Applied Microbiology, Chemistry, Energy Fuels, Environmental Sciences Ecology, Materials Science, Biochemistry Molecular Biology, Food Science Technology and Engineering	Martin-Gil J, Martin-Ramos P, Correa-Guimarães A, Navas-Gracia LM, Hernandez-Navarro S, Sanchez-Bascones M, Muller M, Munne-Bosch S, Del Rio JC, Garcia QS	Brazil, United States of America, Colombia, Panama, Angola, Argentina and Paraguay
United States of America	Engineering, Environmental Sciences Ecology, Plant Sciences, Energy Fuels, Zoology, Agriculture, Biotechnology Applied Microbiology, Evolutionary Biology, Chemistry and Food Science Technology	Berry EJ, Del Rio JC, Gorchov DL, Gutierrez A, Kim H, Ralph J, Rencoret J, Abad-Franch F, Adler HG, and Afonso CAM	Brazil, Spain, Germany, Argentina, Kenya, Panama, Colombia, Netherlands and Portugal

Table 3. Patents on *macaúba* research field from all databases on WoS.

Title	Year	Technology	Process conditions	Substrate	Product	References
Nutrient solution used for cultivation of commercial vegetable, fruits, flowers and microorganisms, comprises bark, leaves and fruit of palmeira such as *Euterpe oleraceae*, *Euterpe edulis*, *Bactris gasipaes* and *Archontophoenix alexandrae*	2015	Grind the substrates to extract the broth and separate the solids from the solution	-	Bark, leaves and fruits of *macaúba* and other species.	Nutritive solution containing nitrogen (N), phosphorus (P) and potassium (K), used for the cultivation of vegetables, fruits, flowers and microorganisms	[192]
Mixture of vegetable oils (*Glycine max*, *Jatropha curcas* and *Acrocomia aculeata*) used as collector for flotation of minerals comprises mixture of soybean oils, Macauba and Jatropha in flotation of ores, in binary and tertiary compositions	2020	The mixture of vegetable oils used in the flotation of ores	-	*Glycine max*, *Jatropha curcas* and *Acrocomia aculeata*	The mixture of vegetable oils used as a collector in the flotation of mineral	[89]
Macaúba (*Acrocomia aculeata*) oil extracted from pulp or kernel of *macaúba*, used as anionic collector in flotation of minerals and as industrial natural reagent	2016	Extraction of oil from pulp or kernel of *macaúba*	-	Pulp or kernel of *macaúba*	*Macaúba* oil as an anionic collector in flotation for the separation of minerals	[90]
Flexible extractor device for use during removal of seeds of trees i.e. *Acrocomia aculeata*, has cylindrical tube and cable provided with protection part, and sharp blades formed with aperture and flow opening and sealed with plastic	2015	The construction of a device to easily remove seeds from *macaúba*	-	-	Flexible extractor device to remove seeds from *macaúba*	[193]
Germinating palm, particularly dormant Acrocomia aculeata involves including five procedures that are obtaining seeds, surface disinfection of seeds, systemic disinfection, total removal of the lid, and incubation	2013 and 2018	Germination method including five procedures: obtaining seeds, surface disinfection of seeds, systemic disinfection,	-	Dormant *Acrocomia aculeata* seeds	Method for germinating palm, especially *Acrocomia aculeata*	[97]

		total removal of the lid, and incubation				
Identifying and separating *Acrocomia aculeata* and *Acrocomia* sp comprises performing synthesis of libraries from samples of macauba, identification of active transcripts, identification of gene microsatellites obtained from primers	2020	Molecular biology techniques	-	*Macaúba* samples, molecular primers and statistical methods	Method for identifying and separating *Acrocomia aculeata* and *Acrocomia* sp.	[98]
Producing activated charcoal used as adsorbent for gaseous and liquid media for purification of undesirable materials, involves crushing fruit endocarp of *Acrocomia aculeata* to obtain carbonaceous powder, and than drying carbonaceous powder	2014	Involves crushing the endocarp to obtain the carbonaceous powder that is dried and immersed inactivating solution. The mixture is heated, washed, filtered and dried; these processes are repeated twice. The dried material was carbonized, washed, filtered and dried to obtain the final product.	-	Endocarp of *Acrocomia aculeata*	Activated charcoal (biochar) for adsorbent purposes	[91]
Method for processing oil used for producing biodiesel, involves preparing fermented solid from fermentation by microorganisms *Rhizomucor miehei* in agroindustrial waste, such as babassu meal and separating oil with low acid content	2016	Solid fermentation of agroindustrial waste with *Rhizomucor miehei.* Lower alcohol is added, and the mixture is kept under stirring.	Temperature: 25-45 °C Added alcohol: methanol or ethanol.	*Macaúba* meal or babassu meal	Method for processing oil used for biodiesel production	[87]
Producing bulk animal feed involves grinding and sieving *macaúba* palm fruit pulp, pressing, extracting to obtain *macaúba* oil, adding to a fermenter under controlled temperature and relative humidity, and then adding supplement	2017	Grinding and sieving *macaúba* fruit pulp. The mixture is pressed and extracted to obtain *macaúba* oil. The mixture with a supplement of urea, glucose, water, inoculum is fermented for 10-120 hours.	0.1-5% urea and/or 0.2-10% glucose; adding water to reach moisture content of 40-80%; and inoculum Temperature: 2-6 °C	*Macaúba* palm fruit pulp	Production of bulk animal feed	[99]

Performing integrated process for production of biodiesel by enzymatic transesterification involves converting *macaúba* oil to biodiesel through use of biocatalyst obtained by solid state fermentation of *macaúba* cake	2019	Integrated process for the production of biodiesel by enzymatic transesterification	Fermentation: inoculated with 107/g microorganism and incubated at 30-40 °C for 24-72 hours. Transesterification: mixing *macaúba* oil with alcohol and triglyceride in the presence of fermented *macaúba* cake. Reacting under stirring at 25- 45 ºC	*Macaúba* oil	Biodiesel	[88]
Active ingredient used in pharmaceutical composition and cosmetics for treating and preventing acute and chronic inflammation, and benign prostate hyperplasia, is obtained from fruits of *Acrocomia crispa* or *Acrocomia aculeata*	2013 to 2020	-	-	Fruits of *Acrocomia crispa*, *Acrocomia aculeata,* or their mixtures	The active ingredient used in a pharmaceutical composition, nutritional supplement and cosmetics	[100]
Organic abrasive used for sandblasting and cleaning plastic components and metal, such as propellers and wheels of aircraft, comprises abrasive material comprising particles of *macaúba* coconut shell in different particle sizes	2013	Milding *macaúba* husks to different particle sizes	-	*Macaúba* husks	Organic abrasive	[96]
Preparing tablet involves using pulp of fruit Acrocomia aculeata as main ingredient, aqueous solution of maltodextrin and water	2017	Food processing for preparing nutritional tablet, using *macaúba* pulp, maltodextrin and water	-	Pulp from *Acrocomia aculeata*	Nutritional tablet	[92]
Manufacturing soap formulation for preparing personal cleaning products, involves harvesting, sterilizing, and pulping fruits of *Acrocomia aculeata*, and then extracting to obtain oil	2014 and 2017	Harvesting, sterilizing and pulping the fruits.	Extracting the oil and directly adding it to glycerin with vitamin E to form a solubilized glycerin base.	Pulps of *Acrocomia aculeata* fruits	Method for manufacturing soap formulation for preparing personal cleaning products	[101]

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